



BELL & HOWELL SCHOOLS

DEVRY INSTITUTE OF TECHNOLOGY

**ALTERNATING CURRENT EFFECTS AND
BASIC AMPLIFIER CIRCUITS**

COURSE 242



ALTERNATING CURRENT EFFECTS AND BASIC AMPLIFIER CIRCUITS

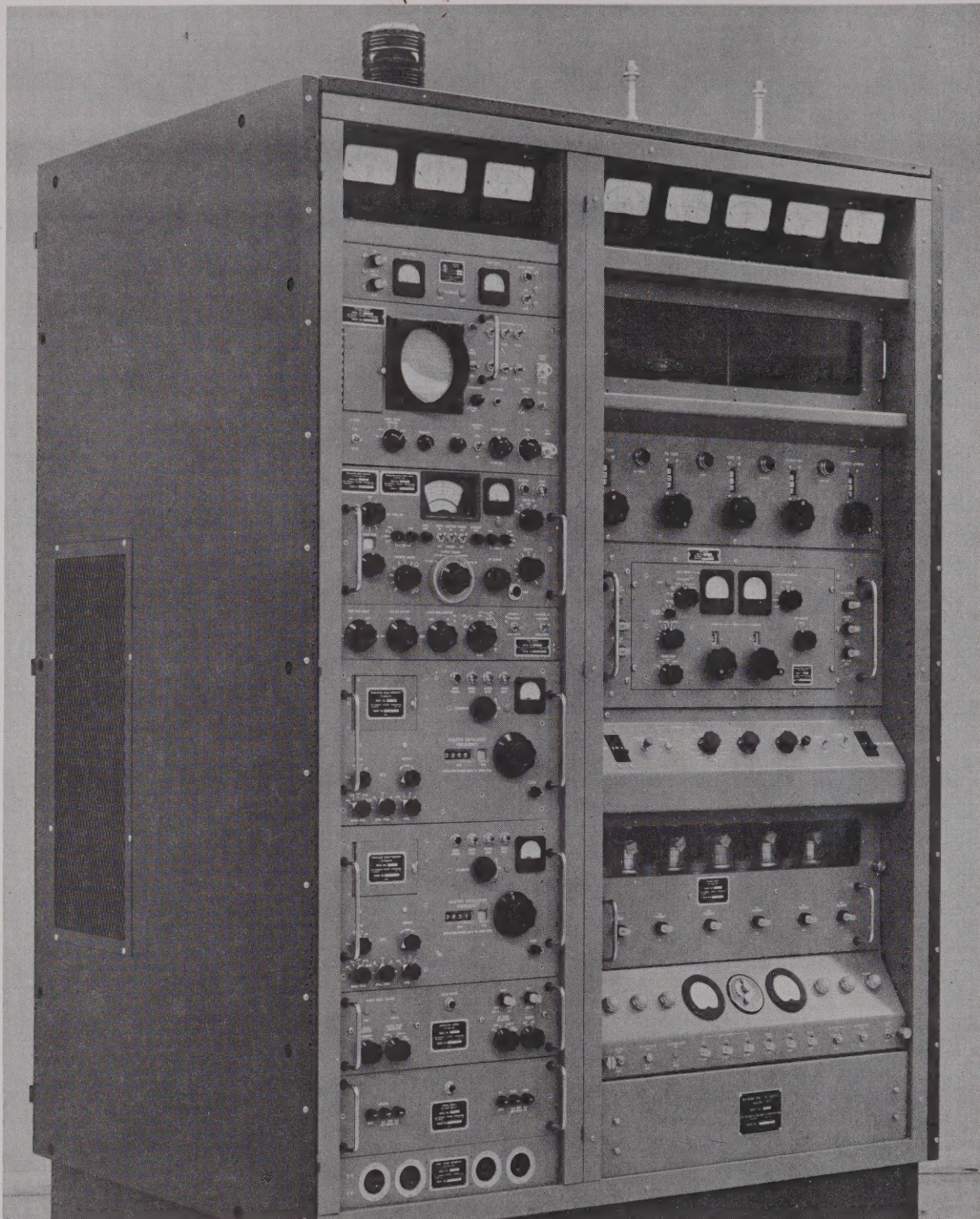
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MEASURING DEVICES

1055

2



Electronic equipment such as this general-purpose transmitter requires constant monitoring while in operation. Current and voltage meters are included as integral parts of the equipment to provide the operator with at-a-glance information concerning critical internal functions.

Courtesy Technical Material Corp.

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*If the control of one's self is the greatest of goals, the control
of one's thoughts is still greater, for what a man thinketh,
so he is.*

—Dr. Frank Crane

MEASURING DEVICES

In this age of technology there is great demand for measurements of many kinds. It is common to measure temperature, voltage, current, resistance, pressure, time and other quantities. Each quantity is measured by some type of instrument, which is usually called a **METER**.

Quantities you work with in electronics are invisible. You cannot see electrons moving through a circuit, nor can you tell by looking at a circuit how much voltage or resistance is present at various points. Thus, electric meters become your eyes.

It is important for you to know how to use electric meters, and also to understand how they work. With this knowledge you will know how to select the proper meter for each job. You will also understand the meaning of the meter readings and the limitations of meters.

METER MOVEMENTS

The **METER MOVEMENT** is the heart of an electric meter. It converts electric energy to mechanical energy to provide a reading on a calibrated scale. Meter movements operate on several transducing principles. However, most of them work on the basic principles of electromagnetism. Understanding the operation of meter movements requires a knowledge of electromagnetism and the properties of an electromagnetic field.

Magnetic Effect

In 1819 Hans Oersted noted that when a compass is brought near a current-carrying conductor, the compass needle is deflected perpendicular (at right angles) to the wire. From Oersted's discovery of the relationships between current and magnetism, we know that an electromagnetic field is generated by current flowing through a wire. The electromagnetic lines of force within this field encircle the wire, as shown in Figure 1A. The direction, either clockwise or counterclockwise, of the electromagnetic field is determined by the **LEFT HAND CURRENT RULE** (Ampere Rule). The Left Hand Current Rule is illustrated in Figure 1A. Note that when the wire is grasped in the left hand with the thumb pointing in the direction of current flow, the curled fingers indicate the direction of the electromagnetic lines of force. In

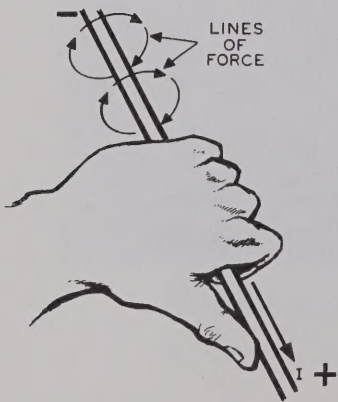


Figure
1

Figures 1B and 1C, the lines of force interact with the magnetic field of the compass in such a way that the compass needle tends to align itself at right angles to the wire.

THE AMOUNT OR DEGREE OF DEFLECTION IS PROPORTIONAL TO (IS A FUNCTION OF) THE AMOUNT OF CURRENT FLOWING IN THE WIRE.

A small current through the wire deflects the compass needle only slightly. A large current swings the needle perpendicular to the wire, which is its maximum deflection. When the current direction is reversed, the compass needle swings in the opposite direction.

The electromagnetic field surrounding a current-carrying wire is perpendicular to the wire and continuous along its entire length. Thus, in Figure 1C the compass needle, while perpendicular to the wire, is PARALLEL to the surrounding electromagnetic field. As shown in Figures 1B and 1C, THE NEEDLE TENDS TO POINT IN THE DIRECTION OF THE ELECTROMAGNETIC FIELD.

Galvanometers

The principles demonstrated in the experiment of Figure 1 were used to construct the first **GALVANOMETER**. Galvanometers are used to indicate or measure small currents in bridge circuits and other sensitive measuring circuits. The arrangement of Figure 1D shows how a simple galvanometer works, using the magnetic principle to indicate the current in a circuit.

To use this arrangement as a meter, the deflection of the needle from its normal position must be calibrated by some sort of number scale. A scale of this type can be made on a sheet of paper under the compass. With a battery voltage of 6 volts, and with R_1 adjusted for a resistance of 6000 ohms, by Ohm's Law, the circuit is now arranged so there is exactly 1 milliamperes of current in it. A number 1 is then written on the sheet of paper in line with the end of the compass needle. R_1 is then adjusted for a resistance of 3000 ohms to give $6/3000$, or 2 mA of current in the circuit. Then a number 2 is written on the paper in line with the new position of the compass needle.

This procedure is continued, increasing the current in the circuit and marking the points where the needle stops each time, until the needle is pointing squarely across the wire. This is as far as the needle can move.

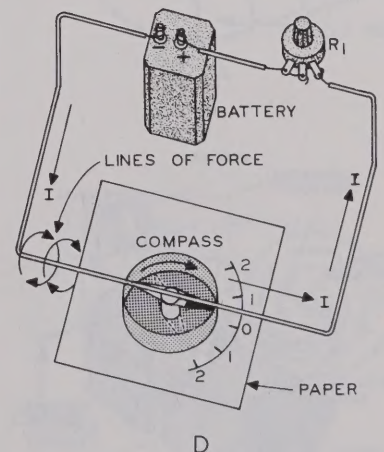
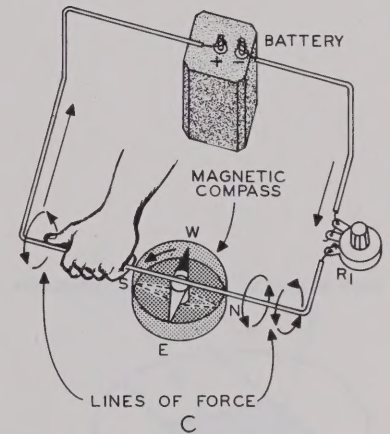
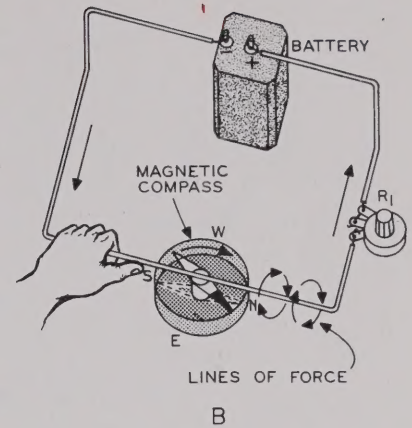


Figure 1

Reversing the current through the circuit will deflect the compass needle in the opposite direction and on the other side of zero. Repeating the same procedure as above, that part of the scale is calibrated in the same way.

When the calibration is complete, the compass needle will indicate the amount and direction of current in the wire. This arrangement is the simplest kind of meter. It indicates the presence of electric current by means of a mechanical motion resulting from the magnetic effect produced by the current.

This type of meter cannot be used for ac measurements, as the quickly reversing current direction would not deflect the meter pointer. The most observable pointer deflection would only be some vibration around the zero-center of the meter scale.

The zero-center scale, by the way, is a distinguishing characteristic of a galvanometer.

Because this galvanometer is calibrated to show the number of amperes flowing in the wire, it can also be called an **AMMETER**. It is a "zero-center" ammeter because the normal resting position of the indicator is at the center of the scale, and currents of opposite direction cause the indicator to move in either direction from this zero point.

The simple galvanometer of Figure 1D is not very practical for normal use because if the position of the compass with respect to the wire or the earth's magnetic field is shifted, the reading will vary. There are other disadvantages to an open meter of this type. When measuring small currents, the magnetic field produced may not be sufficient to overcome the earth's magnetic field. Also, other magnetic fields such as those produced by ordinary house wiring may affect the deflection.

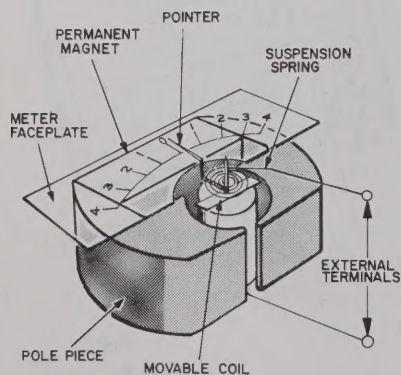


Figure 2

Figure 2 shows an example of how a galvanometer is used as a practical measuring instrument. A movable coil of fine wire with an attached indicating pointer is suspended between two pole pieces. The pole pieces form a low-reluctance path to the poles of a permanent magnet. The coil and attached pointer are suspended between the pole pieces by copper wire springs at the ends of the coil. The suspension provides control over the coil movement and electrical connections between the movable coil and the external circuit.

Current through the movable coil sets up a magnetic field. This field opposes the fixed magnetic field of the pole pieces, causing the coil and attached pointer to deflect from their normal position.

This galvanometer uses the moving-coil principle. Moving-coil meters are the most common instruments in use today. They are built to overcome magnetic and other disturbing effects normally encountered in open-type meters.

Galvanometers may be divided broadly into two classes: those that use a stationary coil and a rotating permanent magnet, and those using a stationary permanent magnet and a rotating coil. The galvanometers which are in widespread use today are the ones in which the coil rotates. These are called **PERMANENT-MAGNET MOVING-COIL (PMMC)** mechanisms. The most widely known meter movement of this type is the **D'ARSONVAL GALVANOMETER**.

D'Arsonval Movement

There are two basic types of moving-coil, or D'Arsonval, mechanisms, which operate on the same principle but are slightly different in design. The basic movement, similar to the one patented by D'Arsonval in 1881, is the EXTERNAL MAGNET type. The other design, developed in recent years with the availability of improved magnetic materials, is the CORE MAGNET type.

The external magnet D'Arsonval moving-coil meter uses a permanent magnet with soft iron pole pieces attached to its ends, as shown in Figure 3A. The pole pieces of the permanent magnet set up a nonuniform magnetic field which is not suitable for meter operation. Therefore, a soft iron core is placed between the pole pieces to develop a uniform magnetic field.

The moving coil, which carries the current to be measured, is shown in Figure 3B. It consists of several turns of fine wire wound on a rectangular aluminum frame. The coil must be light and must be able to swing freely. Thus, only a limited number of turns can be placed on the frame. The indicating needle, or pointer, is attached to the coil and frame. Tiny counterweights are used to balance the assembly on its pivots.

There is a coiled hairspring at each end of the frame. These springs provide flexible electric connections to the moving coil. Also, the springs hold the indicator at the zero scale position when there is no current in the coil. In most meters, the zero scale position is at one side of the meter scale. The

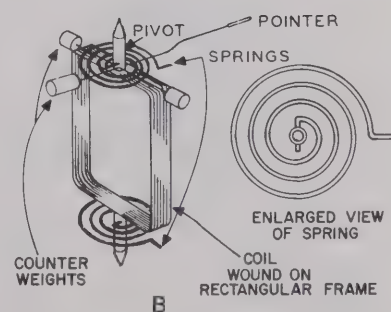
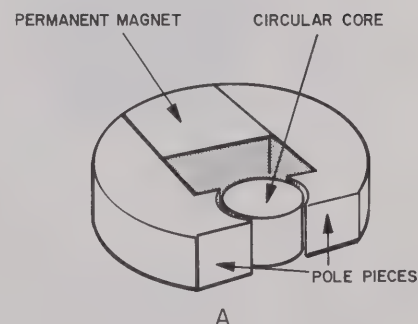
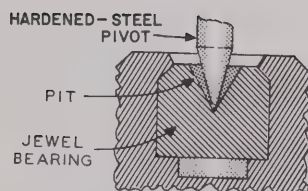
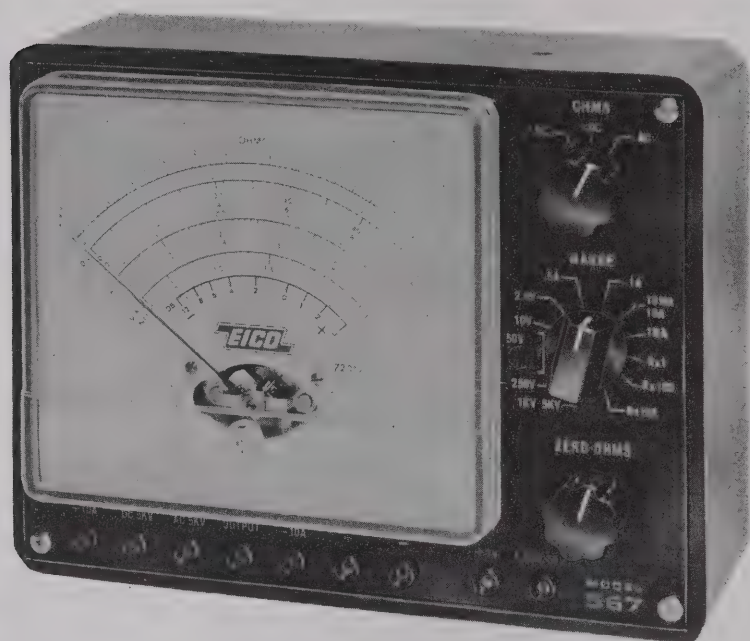


Figure
3

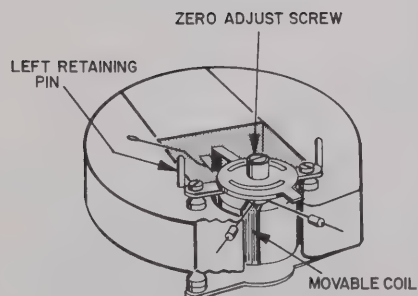
meter pointer deflects from zero in one direction only, rather than in either direction, as it did in the galvanometer.



C

The meter movements used in most commercial instruments today operate on principles discovered by D'Arsonval over 100 years ago. The D'Arsonval movement combines the features of good sensitivity, light weight, ruggedness and linear scale characteristics.

Courtesy Eico Electronic Instrument Co., Inc.



D

Figure
3

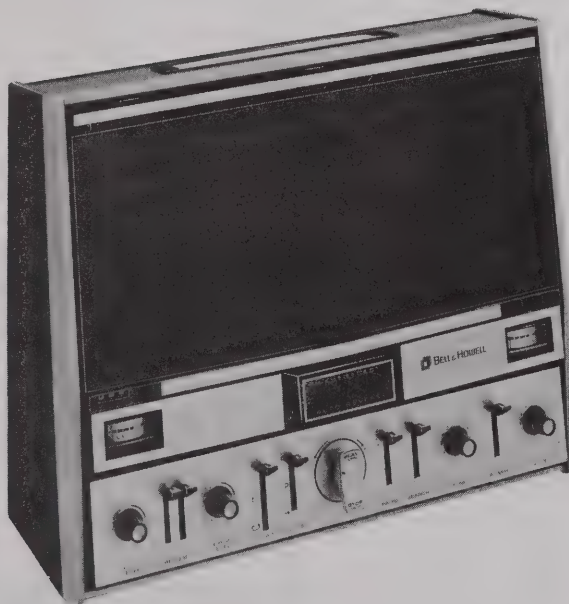
To allow the moving coil to turn freely, hardened steel pivots fitted into jeweled bearings are attached to each end of the frame where the springs are located. This is shown in Figure 3C.

The parts of the D'Arsonval movement are assembled to form a complete meter movement, as shown in Figure 3D. A zero adjust screw on the front of the movement adjusts the pointer for zero scale reading at zero current.

The pointer indicates the amount of current passing through the meter. When a direct current is passed through the coil, the coil sets up its own magnetic poles opposing those of the permanent magnet. As a result, the moving coil is repelled by the permanent magnet. The pointer swings with the coil and registers a reading on the scale. The greater the current, the stronger the magnetic field around the coil, and the farther the pointer and coil rotate.

When current is passed through the meter in the opposite direction, the magnetic field set up by the coil has the opposite polarity. The coil and pointer now are rotated in the opposite direction. This causes the pointer to move backward, hitting the left retaining pin instead of moving to the right across the scale. Therefore, it is necessary to observe the proper polarity when connecting a moving-coil type meter into a circuit.

The pointer must accurately register the amount of current passing through the coil, and it must return to zero when the meter is removed from the circuit. These two actions are accomplished by the control system. The control system consists of the coil springs mounted at each end of the aluminum frame. When the current is passed through the coil, interaction between the magnetic field of the coil and the permanent magnet rotates the moving coil clockwise against the resistance of the spring. When the force of resistance from the spring equals the force of rotation from the action of the magnetic fields, the moving coil and pointer stop. When the meter is disconnected from the circuit, the springs return the pointer to zero. The coil springs also serve to carry current from the external circuit, through the moving coil and back to the external circuit.



The end-pivoted coil (edgewise) mechanism is widely used in recording equipment. The VU (Volume Units) meters shown here are specially-damped ac voltmeters, calibrated in dB.

Courtesy Bell & Howell

The core magnet type meter mechanism shown in Figure 4A is used to obtain the advantages of compact size and weight reduction. In this design, the core itself is a permanent magnet. Such a mechanism is resistant to the effects of external magnetic fields, and thus reduces the need for bulky shield-

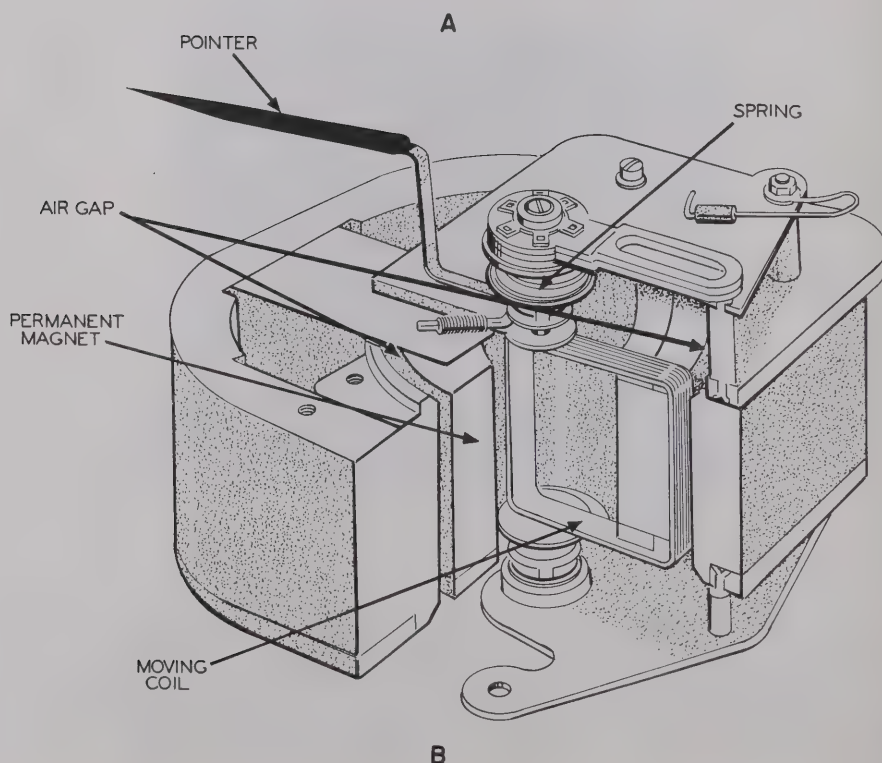
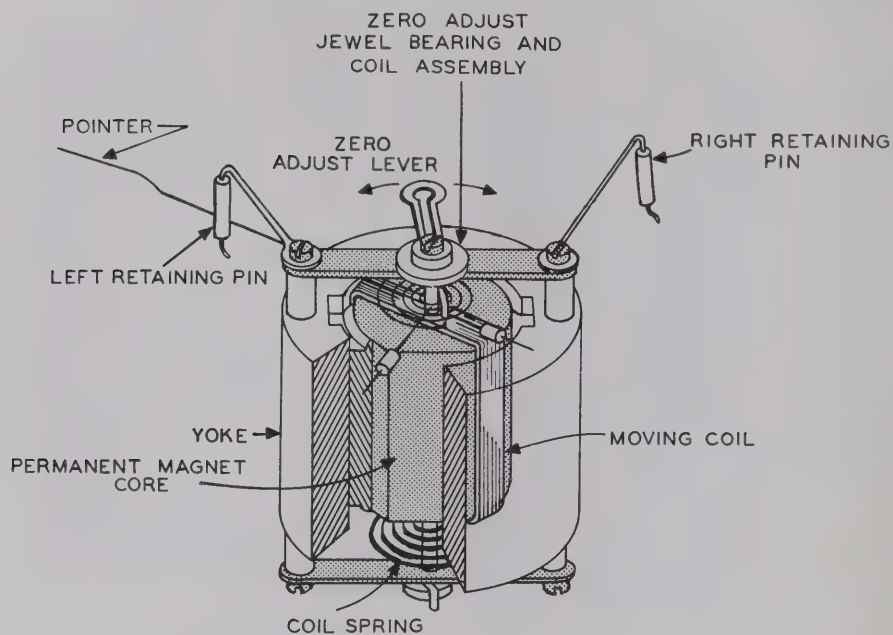


Figure 4

ing materials. The core magnet meter movement is useful in aircraft and aerospace applications where mechanisms are mounted in close proximity to each other. Aircraft instrument panels use core magnet meters in indicators where as many as five mechanisms are mounted in one case to provide a unified display.

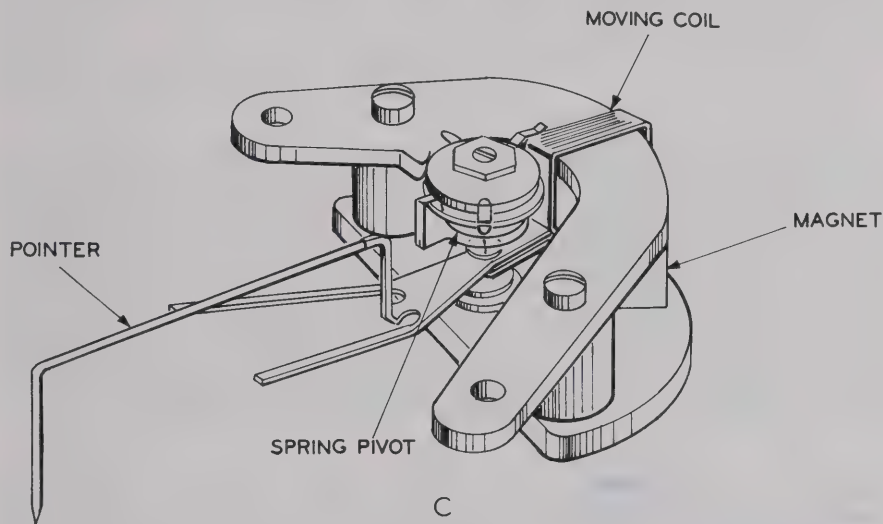


Figure 4

Another type of PMMC mechanism that uses a permanent core magnet is the END-PIVOTED COIL type. In this arrangement (Figure 4B), the coil moves within a single air gap since torque is applied to only one side of the coil. The concept is not new. Movements of this type have been used as far back as 1900, but with low magnetic flux and generally poor performance. However, this movement allows a full-scale deflection of up to 270 degrees rather than 180 degrees as in center-pivoted coils. The end-pivoted type movement is also used extensively in edgewise panel meters (such as VU meters). Deflection in these meters is usually purposely limited to 60 degrees or less with the magnetic flux concentrated over the smaller angle. A typical edgewise meter mechanism is shown in Figure 4C.

Electrodynamic Movement

Electrodynamic mechanisms utilize the fundamental principles of electromagnetism, and are used in a variety of measuring applications. Since neither permanent magnets nor magnetic materials such as iron are used, there are no form or shape variations to affect the mechanism. The electrodynamic

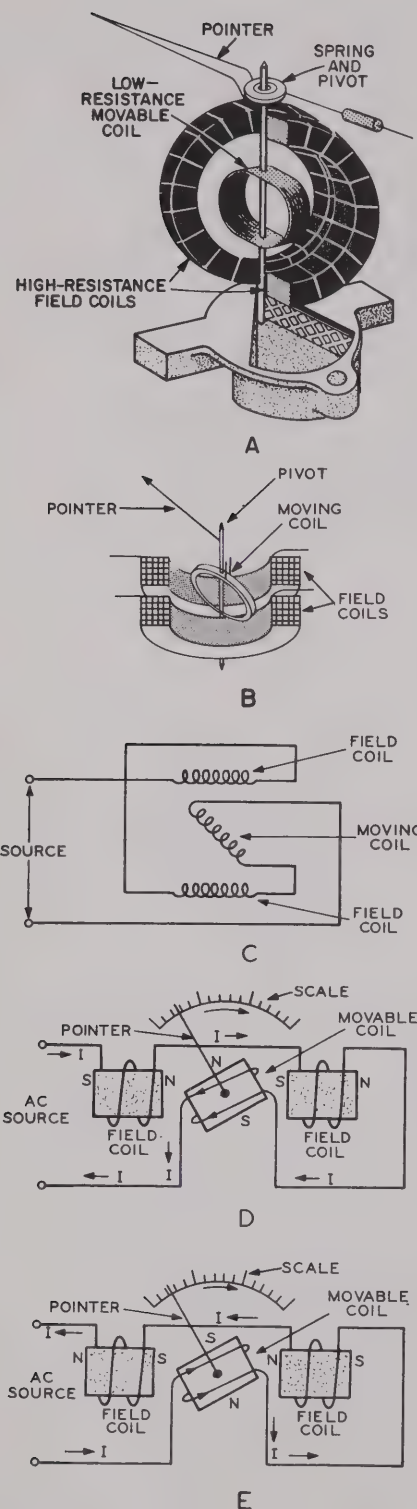


Figure 5

mechanism is current sensitive. That is, the pointer moves because of current flowing through turns of wire which become electromagnets.

Construction of the electrodynamic mechanism is different from that of PMMC movements. Figure 5A shows the actual construction. Two field coils are used in place of a permanent magnet while a movable coil is suspended between and inside them. This arrangement is shown graphically and schematically in Figures 5B and 5C. All three coils are electrically connected in series, as shown in Figure 5C.

The basic idea of the electrodynamic movement can be seen by considering how a permanent-magnet moving-coil movement behaves when measuring ac. Each cycle of alternating current has a positive peak and a negative peak. Therefore, the pointer of the permanent-magnet moving-coil movement will move up-scale the first half of the cycle, or on the positive alternation, and tend to move down-scale on the second half, or negative alternation. At very low frequencies the pointer will swing back and forth around the zero position. At high frequencies the pointer merely vibrates, or oscillates, around the zero point, and no reading is obtained.

This condition can be overcome by replacing the permanent magnet with stationary field coils. This arrangement is shown in Figures 5D and 5E, where the field coils are connected in series with the movable coil. On the positive alternation, current flows in the direction indicated by the arrows in Figure 5D. The current through the field coils sets up a field flux of the indicated polarity around the coils. The current also flows through the movable coil, setting up a field flux opposing that of the field coils.

The north pole of the movable coil is repelled by the north pole of the field coil on the left, and is attracted to the south pole of the field coil on the right. As a result, the pointer moves across the scale to give a reading proportional to the current magnitude.

On the negative alternation the current is reversed in the field coils and movable coil, as shown in Figure 5E. The magnetic fields around the coils also reverse, so the polarities are as shown in Figure 5E. The south pole of the moving coil is repelled by the south pole of the left field coil and is attracted to the north pole of the right field coil.

Notice that the pointer moves in the same direction across the scale for both alternations. Each time the current through the movable coil reverses the field flux also reverses. This maintains the torque in the same direction and causes the pointer to move up-scale on both halves of the cycle.

Electrodynamic mechanisms are used in a general class of instruments called **ELECTRODYNAMOMETERS**. These instruments are the most versatile and basic of all those presently in use since they can be used to measure ac or dc currents, voltages and power. The electrodynamic meter can be used in a variety of ways, as will be shown in the sections of this lesson that cover ammeters, voltmeters and wattmeters.

Electrostatic Movement

The electrostatic type of meter mechanism is similar to a variable capacitor, and is the only device that measures voltage directly. In other words, the mechanism is voltage sensitive rather than current sensitive, as are the electrodynamic and PMMC mechanisms. The force used to move the indicator needle results from the attraction and repulsion caused by a voltage applied between fixed and movable plates. The attraction and repulsion is directly proportional to the voltage between the plates and the plate area; it is inversely proportional to an increasing distance between the plates. In order to obtain the sensitivity required in most applications, the plate areas must be either large or very closely spaced. Since the design of such a device may be limited in these respects, the other method remaining for developing sufficient torque, or force, is to increase the voltage between the plates. This is actually what is done since the electrostatic mechanism is used in **HIGH-VOLTAGE** ac measurements. These instruments are known as **ELECTROSTATIC VOLTMETERS**.

The principle of operation is illustrated by the **GOLD LEAF ELECTROSCOPE** shown in Figure 6A. A very thin, light strip of gold leaf or foil is suspended from a holder in an Erlenmeyer flask or glass jar. A voltage applied to the holder is transferred to the leaf. The ends of the leaf will separate, or stand apart, from each other due to the repulsion of like charges in each arm of the strip. This device is sensitive and will indicate the presence of small voltages. However, the device is only an indicator, and not an instrument. There is no calibrated dial and, therefore, no accurate measurements can be obtained. The electrostatic mechanism is capable of measuring small voltages because there is no high-friction, heavy mechanism to move.

An early instrument using an electrostatic movement was devised by Lord Kelvin in 1887 and is shown in Figure 6B. Moving and fixed plates attract each other, causing the moving plate to rotate against the restoring force of a spring. A modern version of the same mechanism is shown in Figure 6C. The meter is often fabricated in 3½" panel size with multiple sets of plates, and it measures from 150 to 3500 volts.

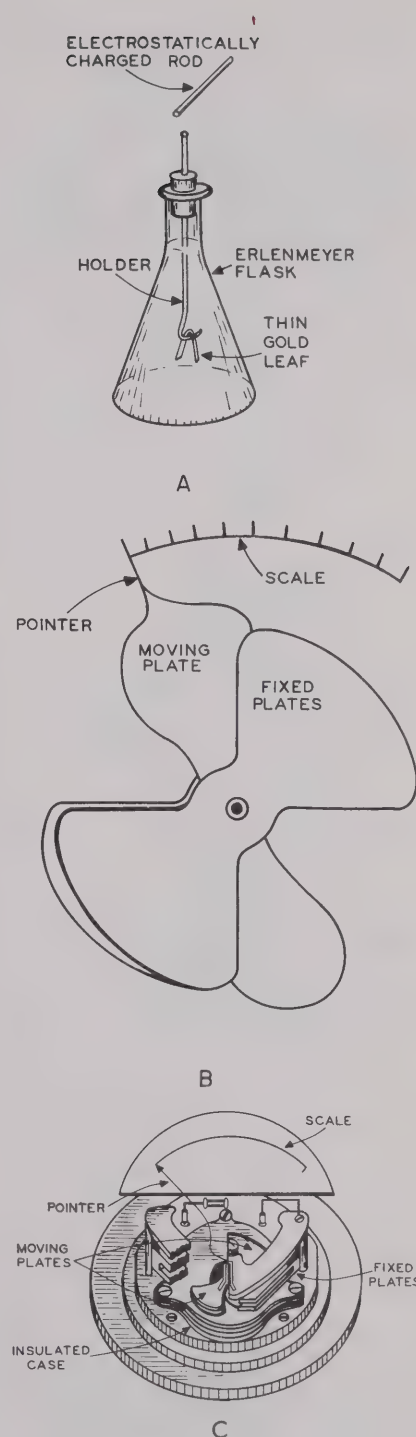


Figure 6

Moving Iron-Vane Movement

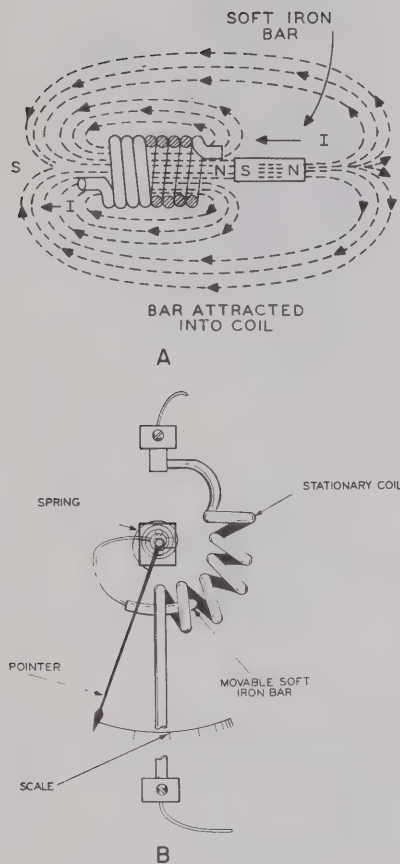


Figure 7

MOVING-IRON METERS operate on the principle illustrated in Figure 7A. A soft iron bar is placed near a coil which is carrying current. This causes the bar to become magnetized, as shown in Figure 7A. The magnetic lines of force around the coil pass through the bar in the same direction as the lines of force induced in the bar by the coil. The lines of force around the coil and bar act like stretched rubber bands trying to shorten themselves, causing the bar to be attracted to the coil, or electromagnet.

As the current in the coil reverses, the lines of force surrounding the coil and bar also reverse. Again the bar is attracted to the coil. Therefore, the bar is attracted to the coil regardless of the direction of current in the coil. The magnetic bar can be attracted to the coil by either dc or ac flowing in the coil. Soft iron is used for the bar, as it demagnetizes readily when the current through the coil ceases.

There are two types of moving-iron meters — the plunger-type and repulsion-type moving vane. The **PLUNGER TYPE** meter is shown in Figure 7B. The movable soft iron bar with a pointer attached at a pivot point is placed

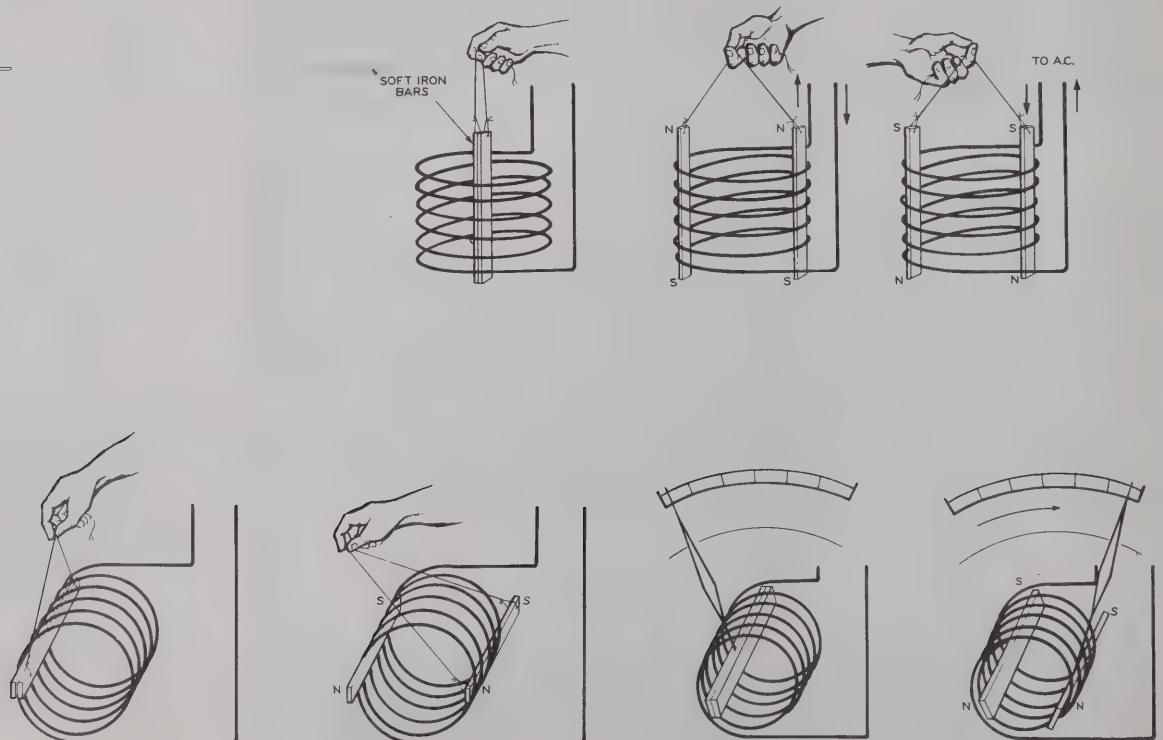


Figure 8

partially inside the fixed coil. Current through the coil sets up a magnetic field. The soft iron bar becomes magnetized and is pulled further into the coil, moving the pointer. The distance the pointer moves depends upon the strength of the magnetic field, which in turn depends on the magnitude of current in the coil.

The basic principle of **REPULSION-TYPE** moving-vane meters is shown in Figure 8. **THE REPULSION-TYPE MOVEMENT**, like the plunger-type, **OPERATES ON THE PRINCIPLE THAT AN ELECTROMAGNET MAGNETIZES SOFT IRON**. Two iron bars are used instead of one, and both are placed completely inside the coil. When current flows, the bars are magnetized with the same polarity. Therefore, with like poles, the bars **MOVE APART**. As current reverses, the polarities of the bars reverse, and they again repel each other.

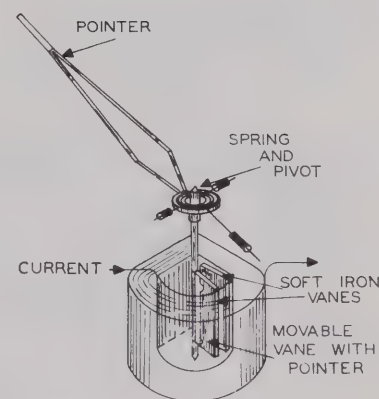
When one bar is fixed and the other is free to move, the force of repulsion can be made to indicate the amount of current flow by attaching a pointer to the movable bar. Note also that the repulsion-type movement can be used to measure either ac or dc.

Two groups of meters use this principle of repulsion. They are the radial-vane and concentric-vane meters. In the **RADIAL-VANE MOVEMENT**, shown in Figure 9A, two rectangular vanes are placed inside the coil. One vane is fixed and the other is free to rotate on pivots. The movable vane has a pointer attached. When current flows through the coil, the iron vanes become magnetized and repel each other. The movable vane rotates on its pivots, carrying with it the pointer that indicates on the scale the amount of current through the coil. The greater the coil current, the greater the pointer movement. The radial-vane movement has **LINEAR SCALE** characteristics. That is, the scale divisions are equally spaced across its length.

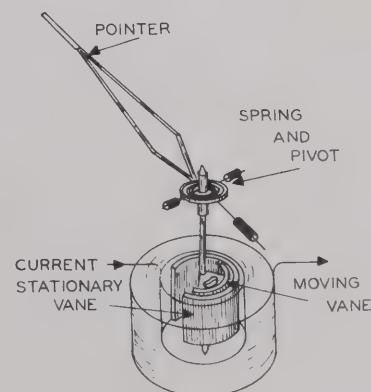
The **CONCENTRIC-VANE MOVEMENT** works on the same general principle as the radial-vane movement. It is described as concentric because the semicircular vanes are placed one inside the other, as shown in Figure 9B. One vane is fixed and the other, with a pointer attached, is free to move on pivots. Repulsion-type meters can be constructed to measure ac and dc, but are generally used to measure low-frequency ac. The concentric-vane movement does not have linear scale characteristics. The scale characteristics are referred to as **NONLINEAR SCALE** or **SQUARE LAW SCALE**.

Square Law Scale

A D'Arsonval meter has a linear scale because the pointer deflection is directly proportional to the current through its moving coil. However, in



A



B

Figure
9

some moving iron-vane meters, hot-wire ammeters and thermocouple ammeters, the pointer deflection is NOT directly proportional to the amount of current flow. In a concentric-vane meter, for example, if the current is doubled, the magnetic field around each vane is twice as strong. Since each vane repels twice as much, the combined repulsion of the two vanes is four times as great.

Thus, the POINTER SWING IN A CONCENTRIC-VANE METER VARIES WITH THE SQUARE OF THE CURRENT. DOUBLING THE CURRENT results in FOUR TIMES THE DEFLECTION. Therefore, deflection is said to be SQUARE LAW. The scale of a square law meter appears nonlinear like the scale of the hot-wire ammeter of Figure 10. The numbers on the low end of the scale are crowded closer together, whereas the numbers at the high end are farther apart.

Hot-Wire Movement

A HOT-WIRE AMMETER movement uses the physical effects of heat generated by current flow in a wire. The physical change in the wire moves a pointer which registers the current in the circuit. Figure 10 shows the basic arrangement. The movement is connected in series with the load through terminals A and B. Inside the meter, wire 1 carries the current. Wire 2 is attached near the center of the current-carrying wire, and pulls on it with a tension controlled by a spring. Wire 2 is wrapped around the round base of a pivoted indicating pointer, and is used as a drive wire for the pointer.

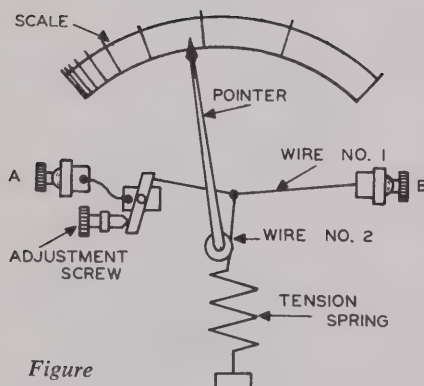


Figure 10

When current passes through wire 1, the wire heats in proportion to the square of the current. The higher the current, the greater the amount of heat generated, and the more wire 1 expands. As wire 1 expands, the drive wire, 2, is pulled down by the tension of the spring. Wire 2, attached to the base of the pointer pivot, drives the pointer across the scale. The pointer is adjusted to read zero with zero current by means of a screw that regulates the normal sag in wire 1.

The hot-wire movement is suitable for use not only at low frequencies, but is also useful at radio frequencies. However, the limitations of this type of instrument are numerous, and have been responsible for its replacement by other types of equipment. The zero setting is indefinite and requires frequent adjustment. It is slow acting and consumes an appreciable amount of energy to produce a readable indication. As a result, it is not as sensitive as other instruments.

Thermocouple Movement

Because of the limitations of hot-wire meters, THERMOCOUPLE AMMETER movements are generally used to measure high-frequency ac. They

The following Practice Exercise questions cover the subjects which you have just studied. They are:

METER MOVEMENTS

MAGNETIC EFFECT

GALVANOMETERS

D'ARSONVAL MOVEMENT

ELECTRODYNAMIC MOVEMENT

ELECTROSTATIC MOVEMENT

MOVING IRON-VANE MOVEMENT

1. What rule is used for determining the direction of an electromagnetic field?
2. The strength of the magnetic field around a current-carrying wire varies with the amount of current in the wire. True or False?
3. In an electric circuit, a laboratory galvanometer indicates the presence of (a) voltage, (b) resistance, (c) current.
4. In the _____ meter movement of Figure 3D, a coil of wire between the poles of a permanent magnet is rotated by the effect of an electric current in the coil.
5. In the moving-coil assembly of Figure 3B, one function of the coiled hair spring is to hold the pointer at the zero position when there is zero current in the coil. True or False?
6. Reversing the current through the coil in the meter movement of Figure 3D has no effect on the direction of pointer motion. True or False?
7. In what type of meter movement is the stationary magnetic field produced by a system of field coils?
8. The electrodynamicometer can be used to measure (a) ac only, (b) dc only, (c) both ac and dc.

9. A mechanism that is voltage sensitive rather than current sensitive is known as (a) electrodynamic, (b) electrostatic.
10. The Gold Leaf Electroscope is an instrument used to obtain accurate measurements of very small voltages. True or False?
11. Attraction and repulsion of electrostatic charges in an electrostatic volt-meter is directly proportional to increasing distance between the plates. True or False?
12. Two basic types of moving-iron meters are the _____ and _____ moving-vane meters.

are used in transmitters to measure antenna current and r-f power. An example of a thermocouple meter is shown in Figure 11.

The heated element in a thermocouple meter movement, shown as wire A in Figure 11, is placed in series with the circuit under test. Wire A is attached to the junction of two different metals, or a bimetallic strip, which forms the thermocouple. The **THERMOCOUPLE** has the property of generating a dc voltage when the junction of the dissimilar metals is heated.

If 1 ampere of current flows through a wire of a certain size, a certain amount of heat is generated. The quantity of heat is exactly the same for 1 ampere of low-frequency ac, high-frequency ac, or dc. The thermoelectric effect, therefore, can be used to measure any kind of current.

The current, I , in Figure 11 heats wire A, which then heats the thermocouple. A small dc voltage is generated and appears across terminals C and D. This voltage is proportional to the amount of heat generated, which is proportional to the current in the circuit.

Within the limits of the thermocouple, the more current in the circuit, the more heat at the junction and the greater the dc voltage generated. The voltage across terminals C and D is then applied to a permanent-magnet moving-coil dc meter. An important point to keep in mind is that either ac or dc can be sent through wire A to heat the thermocouple. Regardless of the kind of current through wire A, only dc voltage appears at the free ends of the thermocouple. The complete unit combines both the thermoelectric and electromagnetic principles of operation.

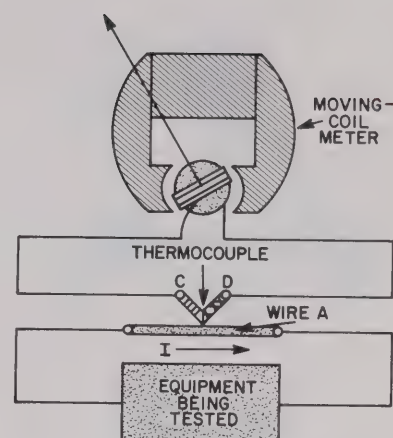
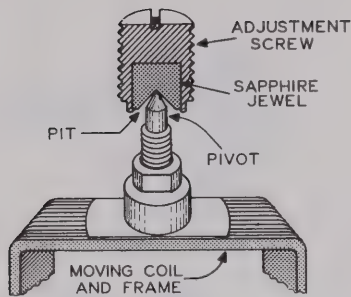


Figure 11

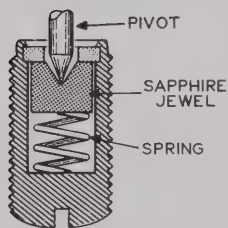
SUSPENSION SYSTEMS

The suspension system of a meter movement allows the moving coil to turn freely on its axis and supports the moving coil in the movement. The coil turns because of the force or torque it produces when its magnetic field opposes that of the permanent magnet. The force required to produce a given amount of motion should be small so that the meter will draw a minimum amount of power from the circuit under test. With less friction in a movement, less power is drawn from the circuit, resulting in a more accurate meter reading. Without a good suspension system, the pointer swings across the scale in a jumping or jerking manner, resulting in poor performance of the movement. Therefore, the problem of supporting the moving coil is very important.

There are several ways in which the coil may be supported. **PIVOT-AND-JEWEL** bearings and **TAUT-BAND** suspensions are the most common.



A



B

Figure
12

Figure 12A shows a typical pivot-and-jewel bearing. The pivot is pressed into a hollow shaft on the frame of the moving coil. This assembly rests in a pit in the sapphire jewel, and the jewel is set into a finely threaded screw for adjustment.

The pivot is made of hardened steel, and the size of the pivot in various instruments depends on the type and weight of the moving coil. The pivot radius varies from 0.0005 to 0.002 inch in most meters. A larger radius can be used to increase the load-carrying capacity of the pivot, but this in turn increases the amount of friction.

Bearings are made of natural sapphire or synthetic jewels. The combination of steel pivot and sapphire gives the lowest friction. Another material used for jewels in some instruments is glass. Glass has the advantage of being relatively cheap and also of being easily shaped.

The radius of the pit in the jewel must be somewhat larger than the pivot. This reduces the amount of friction between the pivot and jewel. The jewel bearing of Figure 12A has the least friction of any commonly used instrument bearing except that of the taut-band suspension system.

Rough handling of an instrument may cause the jewel to crack, or the pivot to deform. This would increase the normal pivot friction and give unsatisfactory operation until repairs are made. Jewels are sometimes spring mounted, as shown in Figure 12B, to lessen the chance of damage from shock.

Pivot-and-jewel bearings present the problem of friction between pivot and jewels, which can cause inaccurate readings. As an instrument grows older, more friction develops and the error becomes greater. Also, pivots and jewels can be damaged by shock, and they can produce sluggish operation if they become dirty.

These problems are minimized in a TAUT-BAND suspension system, shown in Figure 13. Basically, the taut band serves three purposes:

1. supports the moving coil;
2. provides restoring force to resist the force set up by moving-coil current; and
3. carries current to the moving coil.

In a taut-band system, small metal bands, under tension, are used in place of the pivot-and-jewel bearing. An anchor and bumper assembly is used in

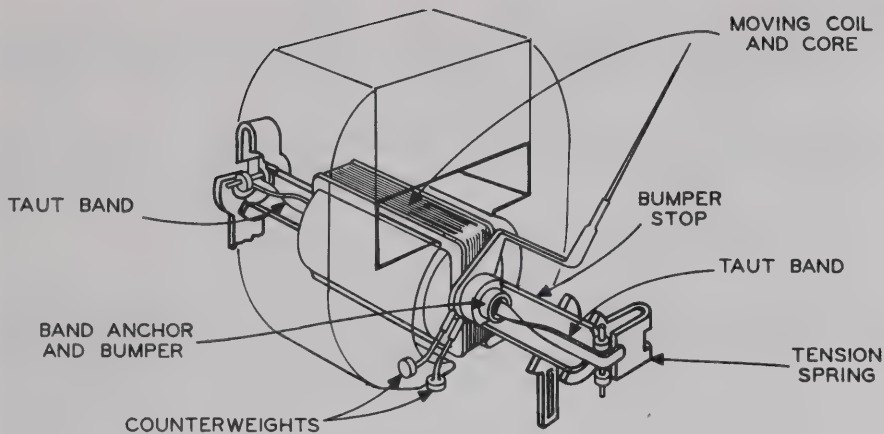


Figure 13

place of the pivot, and a tension spring replaces the jewel bearing. The metal band is now suspended, under tension, between the anchor and tension spring to support the moving-coil assembly.

The bumper and bumper stop limit axial and sidewise motion of the moving-coil assembly in the event of severe shock. One feature of this system is its low level of friction. Also, less power is required from the measured source for full-scale deflection.

The taut-band suspension system has been used in the past in precision laboratory instruments where high sensitivities were required. Often the torques involved were so low that the small frictions of pivot and jewel mechanisms had to be eliminated. Early taut-band movements could be used only in the upright position since the sag in the low torque bands would otherwise cause interference between moving and stationary parts within the instrument. Modern taut-band instruments, however, do not exhibit this disadvantage since the bands are placed under tension. Generally speaking, taut-band suspension instruments can be made with higher sensitivities than those using pivots and jewels, and can be used in any application presently served by pivoted instruments.

DAMPING SYSTEMS

The purpose of DAMPING is to get quick, correct meter readings from the pointer without having it swing back and forth, or oscillate, before coming to rest. We could say that damping acts like a brake for the pointer.

Damping falls into three classes:

1. Underdamped (oscillating). The pointer overshoots the true reading, and then swings back and forth until it settles down to the true reading.
2. Overdamped. The pointer approaches the final position slowly and in a sluggish manner.
3. Critically damped. The pointer comes to its final position in the shortest time that may be obtained without overshooting.

In damping an electrical instrument, it is generally desired to produce a condition close to the critically damped condition. However, the meter should be slightly underdamped so that the pointer overshoots its final position a small amount, then settles back to the reading without any further oscillations. The slight overshoot gives assurance that the instrument is working properly and that the coil and pointer are not sticking.

Damping systems vary with different types of meters. The two most common types are air-vane damping and electromagnetic damping. In an air-vane damping system, a light aluminum vane is mounted on the shaft of the moving element. As the moving element turns, the vane turns at the same time in an airtight chamber, as shown in Figure 14. As the aluminum vane moves, it compresses the air in front of it, causing the pointer to decrease in speed as it approaches its indicating position. When the pointer comes to a stop, there is no further damping or braking action.

In the moving-coil meter, electromagnetic damping is accomplished by the aluminum frame on which the coil is wound. When the coil moves to indi-

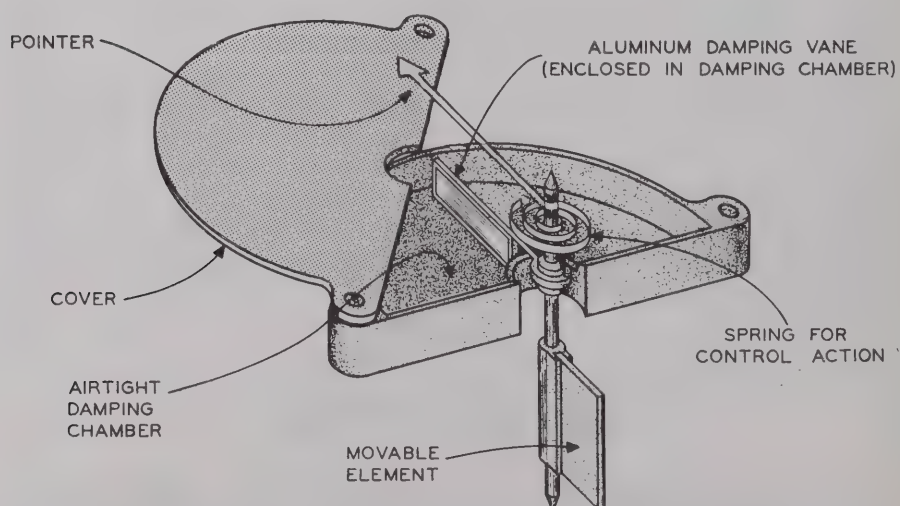


Figure 14

cate current, the aluminum frame itself acts like a one-turn coil. The frame cuts across the magnetic lines of force from the permanent magnet, and as a result, a voltage is induced in the aluminum frame.

The current produced in the frame by the induced voltage sets up a magnetic field which opposes the magnetic field of the permanent magnet. This results in the braking action of the moving coil.

As soon as the coil comes to rest, there is no cutting action. Thus, the voltage is no longer induced in the frame, and it does not produce its opposing field. When the coil returns to the zero position, this process is repeated in the opposite direction, providing braking action for the pointer.

AMMETERS

AMMETERS measure current and are connected in series with the circuit being tested. The resistance of the ammeter must be low to prevent a noticeable decrease in circuit current. The ends of the moving coil are brought out to terminals used to connect the meter into a circuit.

The construction of a given meter determines the range of values it can measure. The number of turns and size of wire of the coil, the physical size of the coil, the strength of the magnet and the strength of the control springs are factors which affect the meter range.

Figure 15 shows a movement requiring a current of 1 ampere in its coil to set up a magnetic field strong enough to move the pointer completely across the scale. The pointer has full-scale deflection at this position, and a number 1 is placed on the scale at this point. Values between 0 and 1 are also marked on the scale. When the scale is calibrated in this way, all that is required to measure any current between 0 and 1 ampere is to connect the meter in series with the circuit and read the value of current from the scale under the pointer.

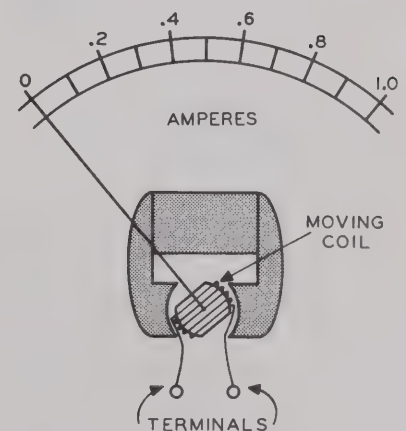


Figure 15

Ammeter Sensitivity

AMMETER SENSITIVITY is defined as THE CURRENT REQUIRED FOR FULL-SCALE DEFLECTION OF THE METER POINTER. An ammeter that requires 1 ampere for full-scale deflection is said to have a sensitivity of 1 ampere. Similarly, a sensitivity of 1 mA means that 1 milliamperere is required for full-scale deflection. Therefore, a 1 milliamperere meter is more sensitive than a 1 ampere meter.

Ammeter Shunts

It was pointed out in the section on electrodynamic mechanisms than an electro-dynamometer can be used as several different types of meters, depending

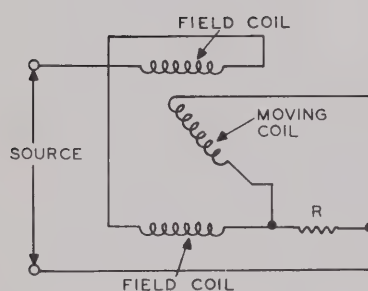


Figure
16

upon the way in which the elements are connected. The electrodynamic meter, as shown previously in Figure 5C, is a simple series circuit between the field coils and the moving coil. This basic arrangement, using no additional resistors or parallel connections, shows an electrodynamic meter used as a **MILLIAMMETER**. A milliammeter is a meter which is calibrated in milliamperes divisions ($1 \text{ milliampere} = 1/1000 \text{ ampere}$). This device is sensitive, and can be used to measure currents of only a few milliamperes. Sometimes a **MICROAMMETER** is used to measure very small amounts of current. A microammeter is a meter which is calibrated in microampere divisions ($1 \text{ microampere} = 1/1,000,000 \text{ ampere}$). This device is extremely sensitive and can be used only to measure currents of a few microamperes. Since all of the current being measured must pass through the low-resistance moving coil, large currents would burn out the coil. We may, however, measure larger currents by adding a low-resistance **SHUNT** resistor, as shown in Figure 16. This resistor is connected in parallel with the moving coil so that when the meter is connected into a circuit, the current divides. Thus, the coil and resistor each carry part of the total current. The shunt can therefore be selected to carry any desired portion of the total current. Consequently, the meter scale can be calibrated to indicate the total current, even though the moving coil carries only a part of it.



Current meters are referred to by their sensitivity ratings. This meter movement is called a microammeter since the instrument is designed for use only in the microampere ($1 \times 10^{-6} \text{ ampere}$) range.

Courtesy Simpson Electric Co.

Shunt resistors may be used with either D'Arsonval or electrodynamic meter movements.

Shunt Calculations

Figure 17 shows an arrangement of a milliammeter, two shunt resistors, and a three-position switch. To calculate the proper shunt resistances, we will assume that the moving coil has a resistance, R_m , of 50 ohms. The required current for full-scale deflection is 1 milliampere (.001 ampere). With the switch in the 1 mA position, as shown in Figure 17, the shunts are disconnected. Thus, the moving coil carries the entire current between the negative and positive meter terminals. A circuit current of 1 mA causes full-scale deflection of the meter pointer.

Moving switch S_1 to the 10 mA position connects shunt R_1 across the moving coil, providing two parallel current paths between the meter terminals. For full-scale deflection, the meter movement must still carry its maximum current of 1 mA. With a full-scale value of 10 mA applied to the meter movement and shunt in parallel, the shunt must carry the difference between 10 mA and 1 mA, which is 9 mA (.009 ampere).

With a 1-mA (.001 ampere), 50-ohm moving coil, the resistance of shunt R_1 , for a 10 mA range, can be found. Using Ohm's Law, the voltage across the coil, E_m , is .001 times 50, or .05 volt. Since the coil and R_1 are in parallel, the voltages across them are the same. Therefore, we know the voltage across and the current through R_1 . According to Ohm's Law, the resistance of R_1 is:

$$R_1 = \frac{.05}{.009} = 5.55 \text{ ohms.}$$

Turning switch S_1 to the 100 mA position disconnects R_1 and connects R_2 across the moving coil. For the 100 mA range the current through R_2 is 100 — 1, or 99 mA (.099 ampere). Since the voltage is still the same across the coil for this range, E_2 is .05V and R_2 is:

$$R_2 = \frac{.05}{.099} = .505 \text{ ohm.}$$

This is the shunt resistance calculated for the 100 mA range for a 1-mA, 50-ohm moving coil.

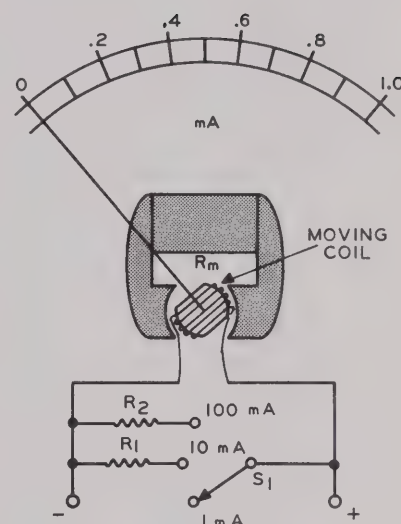


Figure
17

Regardless of its magnitude, the current always divides between the moving coil and shunt in exactly the same ratio. Referring again to Figure 17, R_1 carries nine times as much current as the moving coil. That is, with a total current of 10 mA, shunt R_1 carries 9 mA and the moving coil 1 mA. When the total current is reduced to 8 mA, the moving coil carries .8 mA and the shunt carries nine times .8 mA, or 7.2 mA. If the total current is 4 mA, the moving coil carries .4 mA and the shunt carries nine times .4 mA, or 3.6 mA.

Thus, with R_1 in the circuit, the coil always carries one-tenth of the total current. This can be indicated directly on the scale by moving the decimal points so the scale reads the total current instead of the current through the coil. In Figure 17, the scale divisions for the 10 mA range would be 0, 2, 4, 6, 8, 10. With shunt R_2 in the circuit, the moving coil carries one-hundredth of the total current. This can be indicated by marking the scale of Figure 17 to read 0, 20, 40, 60, 80, 100.

Although shunts are used to EXTEND the range of the meter, they cannot be used to make the meter indicate by full-scale deflection a current lower than that for which the meter movement was designed. Thus, a shunt can decrease the sensitivity of a meter but can never increase it.

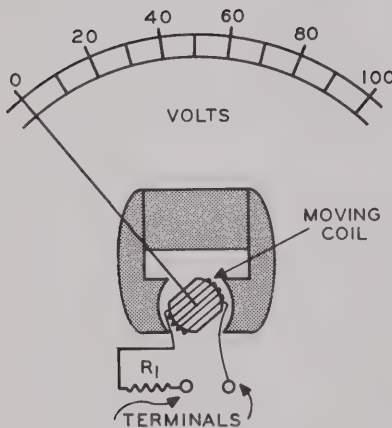


Figure 18

DC VOLTMETERS

The D'Arsonval movement used as an ammeter in Figure 15 can also be used as a **VOLTMETER**, as shown in Figure 18. The meter scale is now calibrated to read voltage when the moving coil leads are paralleled with a circuit through current-limiting resistor R_1 .

A D'Arsonval movement is operated by the magnetic effect of an electric current in its coil. A voltmeter is actually operated by the current through its coil. The scale is calibrated to read the voltage required across its terminals to cause a given amount of meter pointer deflection.

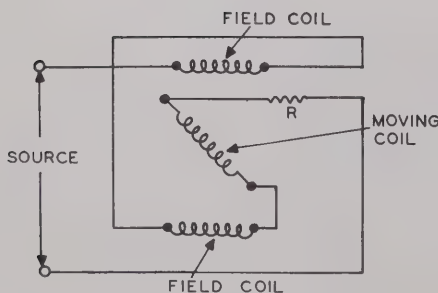


Figure 19

The basic electrodynamic circuit shown in Figure 5C can also be used as a voltmeter. Just as the basic series circuit required a shunt resistor to measure larger currents, the same circuit, with the addition of a SERIES-LIMITING resistor, can be used to measure larger voltages. When connected as shown in Figure 19, the circuit becomes a voltmeter. The limiting resistor is placed in series with all three coils, and the components form a complete series circuit. Although the shunt resistor in an ammeter has a low-resistance value, the series-limiting resistor in a voltmeter has a high-resistance value. Just as with a D'Arsonval voltmeter, an electrodynamic voltmeter is

The following Practice Exercise questions cover the subjects which you have just studied. They are:

METER MOVEMENTS

SQUARE LAW SCALE

HOT-WIRE MOVEMENT

THERMOCOUPLE MOVEMENT

SUSPENSION SYSTEMS

DAMPING SYSTEMS

AMMETERS

AMMETER SENSITIVITY

AMMETER SHUNTS

SHUNT CALCULATIONS

13. Meters which register according to the square law rather than in direct proportion to the amount of current flow are (a) moving-coil meters, (b) moving-vane meters.
14. Hot-wire ammeters depend on what physical effect to register current in an electric circuit?
15. The thermocouple meter is only capable of measuring direct current. True or False?
16. What purpose does the suspension system serve in a meter movement?
17. Pivot-and-jewel bearings are sometimes spring mounted to lessen the damage from shock. True or False?
18. Compared to pivot-and-jewel bearings, the friction in taut-band suspension systems is (a) greater, (b) less.
19. Damping in a meter movement acts like a brake for the moving coil and pointer. True or False?
20. The two types of damping used in electric meters are _____ and _____ damping.
21. The coil resistance must be high in a meter movement that serves as an ammeter. True or False?

22. Compared to a milliammeter with a sensitivity of 1 milliampere, a 1-ampere ammeter has (a) a greater sensitivity, (b) less sensitivity, (c) the same sensitivity.
23. A milliammeter has a sensitivity of 10 mA. What is the minimum amount of current required to deflect the pointer to full scale?
24. Assume that the ammeter of Figure 17 has a coil resistance of 100Ω and requires 1 mA for full-scale deflection. What are the values of shunt resistors R_1 and R_2 to provide ranges of 10 mA and 100 mA, respectively?
25. Shunts can be used to make a meter indicate lower currents than those for which the meter movement is designed. True or False?

connected in parallel with the voltage to be measured. Because the meter is current sensitive, it is necessary to limit the current flowing through the moving coil to a safe level when connecting the meter to measure voltages. The current divides at the point of measurement when the voltmeter is placed in parallel with the circuit under test, and the amount of current through the moving coil will be small if the series-limiting resistor is large.

Voltmeter Sensitivity

The sensitivity of a meter movement is a measurement of the current required for full-scale deflection. Meters that require low current for full-scale deflection of the pointer are more sensitive than meters that require high current for the same deflection. Most voltmeters use movements of relatively high sensitivity, as a sensitive movement requires little current from the circuit under test and disturbs circuit operation less, producing less error in the reading.

Instead of referring to the sensitivity of voltmeters in terms of the current required for full-scale deflection, it is common to state the voltmeter sensitivity in terms of ohms-per-volt (ohms/volt). This means that the meter circuit resistance is a certain number of ohms for each volt, at full-scale deflection. In Figure 18, assume that the total resistance of the meter circuit is 100,000 ohms for a full-scale reading of 100 volts. Thus, its sensitivity is 100,000 ohms divided by 100 volts, or 1000 ohms/volt. A meter movement that operates with less current for full-scale deflection requires more resistance in the meter circuit, and its ohms/volt rating is higher. Thus, the greater the sensitivity, the higher the ohms/volt rating of the meter.

The ohms/volt rating of any meter can be calculated by dividing 1 by the full-scale current rating of the meter. Thus:

$$\text{ohms-per-volt} = \frac{1}{\text{full scale current}}$$

For example, a meter requiring 1 mA for full-scale deflection has an ohms-per-volt rating of 1/.001, or 1000. If the meter movement of Figure 18 required 100 microamperes (.0001 ampere) for full-scale deflection, the sensitivity rating would be:

$$\frac{1}{.0001} = 10,000 \text{ ohms-per-volt.}$$

Voltmeter Multipliers

A voltmeter is basically an ammeter with a series resistance to limit the current through the meter movement. Thus, we can adapt the ammeter of Figure 15 to operate as a voltmeter. Let us assume that the moving coil has a resistance of 50 ohms and requires a current of 1 mA for full-scale deflection.

When connected directly across any two points of different potentials, the resistance of the voltmeter circuit must be high enough to limit the current to that required for full-scale deflection. Therefore, resistor R_1 is connected in series with the moving coil; R_1 is called a **MULTIPLIER** resistor, or simply, a multiplier.

Let's determine what is required to permit the voltmeter of Figure 18 to indicate a maximum potential of 100 volts. One milliamperere of current in the moving coil produces full-scale deflection. Therefore, the total resistance of R_1 plus the resistance of the moving coil, which is 50 ohms, must be such that the current is limited to 1 milliamperere when 100 volts is applied. Substituting the known current and voltage into Ohm's Law, the total resistance must be:

$$\begin{aligned} R_T &= \frac{E}{I} \\ &= \frac{100}{.001} \\ &= 100,000 \text{ ohms.} \end{aligned}$$

The value of R_1 can be determined by subtracting the resistance of the moving coil from the total resistance: $100,000 - 50 = 99,950$ ohms. Then, with 100 volts across the terminals, the voltage is across a total resistance of 100,000 ohms, and the current is $100/100,000$, or 1 milliamperere, for full-scale deflection of the pointer. Thus, a number 100 is marked on the high end of the scale.

Additional values between 0 and 100 can be located on the scale by applying different voltages to the terminals and marking the scale accordingly. For example, with 50 volts applied to the terminals, the number 50 can be marked on the scale where the pointer stops. After the scale is calibrated, any potential between 0 and 100 volts can be measured merely by applying it to the meter terminals and reading the indicated voltage.

A single range voltmeter is limited in application. If 2 or 3 volts is applied to the 100-volt meter of Figure 18, the resulting pointer deflection is so small that it is difficult to read on the scale.

A multi-range voltmeter is convenient for measurement of voltages ranging from a fraction of a volt to several hundred volts. To obtain multi-range operation, a single meter movement is supplied with several multipliers, arranged so that the proper one can be selected by means of a switch or by using separate terminals. For example, in Figure 20, multipliers R_1 , R_2 , R_3 and R_4 are connected in series between the moving coil and the 1000-volt terminal. The junctions between the resistors are connected to additional terminals to provide ranges of 10, 100, 500 and 1000 volts. With one test lead connected directly to one end of the moving coil (the negative terminal of the meter), the desired voltage range is selected by connecting a second test lead into one of the four other terminals. DC voltages of either polarity can be measured by simply reversing the leads to the circuit.

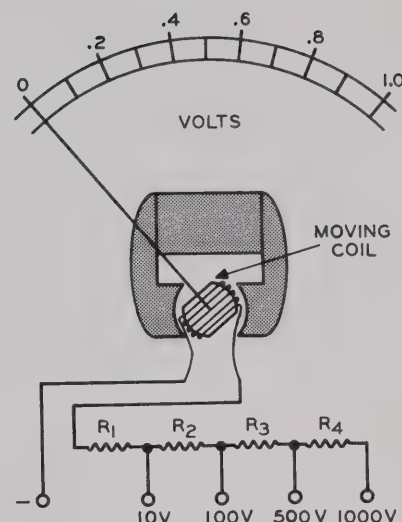


Figure 20

RECTIFIER-TYPE AC VOLTMETERS

As we learned earlier, a Permanent-Magnet Moving-Coil mechanism such as the D'Arsonval movement cannot be used to measure ac. This was discussed in the section on electrodynamic meter movements.

It was pointed out that in trying to measure ac with a PMMC movement, the pointer would merely vibrate or oscillate around the zero point, and no reading would be obtained. This is because the current through the moving coil constantly changes direction, thus reversing the polarity of the electromagnetic field. This effect can be overcome by using a FULL-WAVE BRIDGE in the meter circuit, thus maintaining current in one direction through the moving coil. As shown in Figure 21, an ac voltage is impressed across a circuit consisting of diodes D_1 , D_2 , D_3 and D_4 , the moving coil, and resistor R_1 .

Current flow for each positive half cycle divides as shown by the solid arrows in the figure. Current flow for the negative half cycles is shown by the dashed arrows. The diodes in the circuit permit conduction through the meter movement in only one direction. Therefore, the electromagnetic field generated by the current maintains constant polarity, and the meter functions in the same way as when measuring dc.

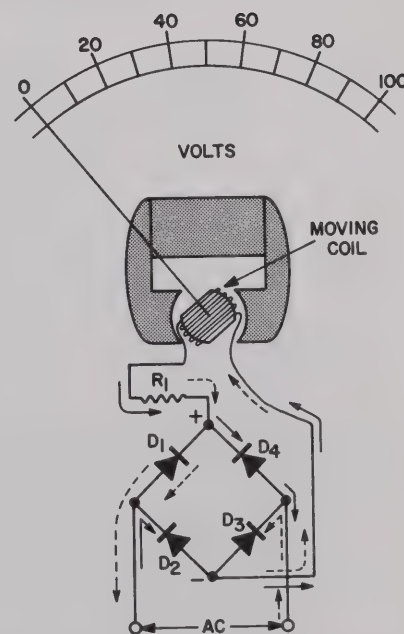
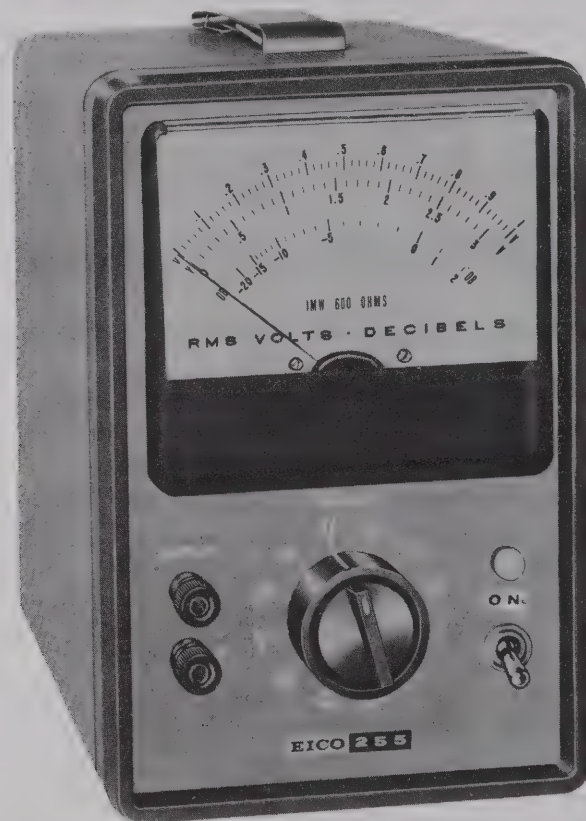


Figure 21

The diodes provide full-wave rectification through the meter movement, and pointer deflection caused by the current through the moving coil is the

AVERAGE VALUE of the alternating voltage. The meter scale, however, is calibrated to provide readings in rms volts, the most widely used and accepted measure of sinusoidal ac. The rms (Root Mean Square) value, however, is actually the EFFECTIVE VALUE of an alternating current or voltage, and not the average value. We may literally say, that a sinusoidal current or voltage is only .707 times as effective as an equal amount of direct current or voltage. Therefore, the effective or rms value of a sinusoidal waveform is .707 of the peak value.



AC voltmeters are generally calibrated in RMS (Root Mean Square) volts, since this is the most widely used measure of ac.

Courtesy Eico Electronic Instrument Co., Inc.

The average value of alternating currents and voltages is .637 of the peak value, which is less than the rms. However, since the ratio between rms and average values is a constant, the meter may be calibrated to read rms volts.

Multiplier Calculations

The current required to operate a voltmeter must be supplied by the circuit under test. Therefore, to cause the least possible change in circuit conditions, voltmeter current must be low. For this reason, the movements in most voltmeters used with electronic equipment require very little current for full-scale deflection of the pointer.

The multi-range voltmeter of Figure 20 uses a 1 mA meter movement which has a resistance of 50 ohms and a sensitivity of 1000 ohms-per-volt. To demonstrate the multiplier calculations, the resistances of R_1 , R_2 , R_3 and R_4 will be determined. Although Ohm's Law can be used directly in these calculations, the ohms-per-volt rating of the meter makes the calculations simpler.

As shown in Figure 20, for the 10-volt range the multiplier is R_1 , for the 100-volt range it is $R_1 + R_2$, for the 500-volt range it is $R_1 + R_2 + R_3$, and for the 1000-volt range it is $R_1 + R_2 + R_3 + R_4$. Because R_1 is part of all the multipliers, its value can be calculated first. Next R_2 , then R_3 and finally R_4 can be determined.

Because there must be 1000 ohms-per-volt for full-scale deflection, the total resistance between the minus (—) and 10V terminals must be 10 times 1000, or 10,000 ohms. The total resistance of a series circuit is equal to the sum of the individual resistances. Therefore:

$$R_T = R_m + R_1;$$

where: R_m is the resistance of the meter movement.

This can be rearranged to solve for R_1 :

$$\begin{aligned} R_1 &= R_T - R_m \\ &= 10,000 - 50 \\ &= 9950 \text{ ohms.} \end{aligned}$$

For the 100V range, the total resistance must be 100×1000 , or 100,000 ohms. From the previous calculations, $R_m + R_1$ was found to be 10,000 ohms. Therefore:

$$\begin{aligned} R_2 &= R_T - (R_m + R_1) \\ &= 100,000 - 10,000 \\ &= 90,000 \text{ ohms.} \end{aligned}$$

This same procedure is followed in calculating R_3 and R_4 . For the 500V range:

$$\begin{aligned} R_3 &= R_T - (R_m + R_1 + R_2) \\ &= 500,000 - 100,000 \\ &= 400,000 \text{ ohms.} \end{aligned}$$

For the 1000V range:

$$\begin{aligned} R_4 &= R_T - (R_m + R_1 + R_2 + R_3) \\ &= 1,000,000 - 500,000 \text{ ohms} \\ &= 500,000 \text{ ohms.} \end{aligned}$$

OHMMETERS

It is often necessary to determine the resistance of a circuit or component. Resistance can be measured in several ways, but the simplest and most popular way is to use a meter that reads directly in ohms.

Ohm's Law shows that with a constant voltage applied to a circuit, the current varies inversely with the resistance. Thus, if a known voltage is applied to a device and the current is measured by a current meter, the pointer will deflect according to the resistance. Resistance readings can be marked on the scale instead of current readings. When the scale is calibrated directly in ohms, the instrument is called an **OHMMETER**.

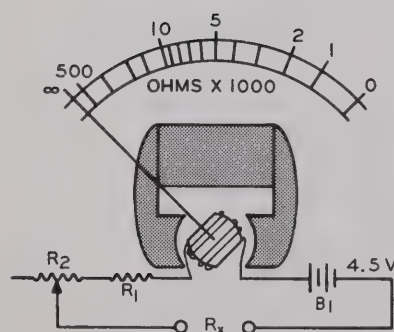


Figure
22

The **SERIES OHMMETER** of Figure 22 includes the same meter movement that was used previously, but the meter scale is now calibrated in ohms.

In Figure 22, the scale of the ohmmeter is a **NONLINEAR SCALE**. Zero ohms is at the right end of the scale, and moving to the left across the scale the divisions become closer together. The extreme left end of the scale is marked infinity (∞). This represents a resistance beyond the range of the meter. The circuit includes a battery as a voltage source, the moving coil of the meter, fixed resistor R_1 , variable resistor R_2 , and two external terminals. When an unknown resistance, R_x , is connected between the terminals, a series circuit is completed and the resulting current causes a deflection of the meter pointer.

As the meter requires 1 mA for full-scale deflection, and a 4.5-volt battery is indicated, the circuit must include 4500 ohms of resistance to prevent ex-

cessive current when the R_x terminals are shorted. The total resistance consists of the moving coil, fixed resistor R_1 , and variable resistor R_2 . Resistor R_2 is called the ohmmeter Ohms Adjust control. It is made variable to compensate for voltage variation as the battery ages.

Although a single variable resistor could be used in place of R_1 and R_2 , its adjustment would be extremely critical because of its wide range. With the arrangement shown, a fixed resistor of approximately 3500 ohms, the meter resistance of 50 ohms, and a variable resistor of 1000 ohms are placed in series. Thus, the circuit resistance can be varied from slightly above to almost 1000 ohms below the required 4500 ohms by adjusting R_2 , and the adjustment is not critical. Moreover, by having a minimum of 3500 ohms resistance in the circuit, the possibility of an excessive current burning out the meter movement is reduced.

The R_x terminals are in series with the battery, moving coil and resistors. If the terminals are shorted and the circuit is adjusted to place 4.5 volts across 4500 ohms of resistance, by Ohm's Law this condition allows 1 mA of current and the pointer moves all the way across the scale. Now, suppose a resistor of 1000 ohms is connected across the R_x terminals. The total resistance of the meter circuit is then increased from 4500 ohms to 5500 ohms, and the meter will indicate a current of $4.5/5500$, or .000818 ampere (.818 mA). When calibrating the scale, 1000 ohms is marked at this position since 1000 ohms is the resistance added to the circuit to cause this amount of pointer deflection.

Using the same procedure, resistors of 2000, 5000, 10,000 and 500,000 ohms can be connected between the R_x terminals, and the resistance values can be marked on the scale where the pointer comes to rest for each resistor. Precision resistors designed for calibration purposes must be used to get an accurate calibration of the scale. Having marked the scale at intervals with known resistance values, unknown resistances can then be read directly from the scale.

Another type of ohmmeter, shown in Figure 23, is referred to as a **BACK-UP OHMMETER**. It receives its name from the fact that when resistance is measured, the pointer moves in a direction opposite to that of most other types of meters. To obtain back-up operation, the 4.5-volt battery, the meter movement, resistors R_1 and R_2 , and switch S_1 are all connected in series, and the R_x terminals are attached to each end of the moving coil. With this arrangement, any resistor connected between the R_x terminals is shunted across the moving coil and reduces the meter reading. Switch S_1 is included so that the circuit may be turned off to prevent the battery from discharging when the meter is not in use.

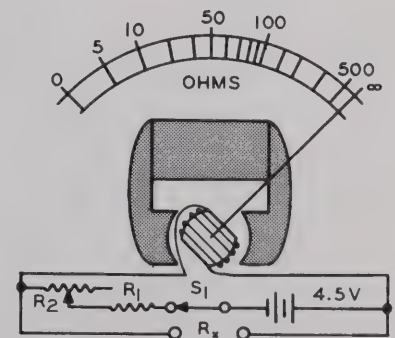


Figure
23

With the switch closed and nothing connected across the R_x terminals, the circuit is the same as that of Figure 22 with the R_x terminals shorted. Thus, there is a full-scale deflection of the meter pointer and the infinity symbol (∞) is placed at the right end of the scale. The zero reading is at the left, as a short between the R_x terminals would prevent current through the meter movement and would therefore cause zero pointer deflection.

Let us assume that the moving coil in Figure 23 has a resistance of 50 ohms and requires 1 mA for full-scale deflection. With a 50-ohm resistor connected between the R_x terminals, the circuit current, still approximately 1 mA, will divide equally between the moving coil and resistor. This gives a moving-coil current of approximately .5 mA, and the pointer will stop at the halfway point on the scale. This point can be marked 50, for in this case the "unknown resistance" is 50 ohms.

This is an interesting point to remember. The center marking of any back-up scale ohmmeter indicates the internal resistance of the moving coil unless shunts are internally connected across the moving coil. In that case, the center scale marking indicates the combination of resistances.

A back-up ohmmeter is calibrated in the same way as a series ohmmeter. However, because the resistance of the moving coil is comparatively low and because it determines the mid-scale value, the circuit of Figure 23 is used mainly for measurement of low resistance.

The circuit of Figure 22 is more flexible, as the resistance ranges can be varied to take care of any practical measurement. The range depends not only on the sensitivity of the meter movement, but also on the supply voltage. Although a battery is shown, any source of dc voltage can be employed. For example, in a number of commercial units, a dc voltage is obtained from an ac power outlet by employing a rectifier built in as a part of the ohmmeter circuit.

Before making tests, the terminals of the series-type ohmmeter of Figure 22 are shorted and variable resistor R_2 is adjusted until the meter pointer indicates exactly 0 at the right edge of the scale. Then the short is removed, and the value of an unknown resistance connected to the R_x terminals will be indicated on the scale.

For the back-up meter of Figure 23, the R_x terminals are left open and, with switch S_1 closed, resistance R_2 is adjusted until the pointer deflects full scale to the ∞ mark. Then the value of an unknown resistance connected between the R_x terminals will be indicated on the meter scale.

MULTIMETERS

One of the most useful of all measuring devices is the Volt-Ohm-Milliammeter (**VOM**), or **MULTIMETER**. This instrument combines the circuits of ac and dc voltmeters, ohmmeters and milliammeters. Note that, in Figure 24A, the circuits are similar to those already presented in this lesson and are easily recognizable. There are four ranges each for ac and dc volts. The ac volts circuit is the bridge rectifier type. The meter also includes four ranges for resistance measurement, three for milliamperes and one for microamperes. A 17-position switch connects the various circuits to the meter movement. In analyzing a circuit for a given function or switch position, assume that the four switch arrows move simultaneously and may be placed on the contacts opposite the desired function and level numbers. The $V\Omega A$ and COM. terminals at the bottom of the diagram are the inputs to the meter. The leads, or probes, provide the input voltages and resistances to the meter circuits. A red or colored lead is used with the $V\Omega A$ input, and a black lead with the COM. input. As was pointed out earlier in this lesson, the meter uses a dc movement, and proper polarity must be observed for dc measurements. The meter will read positive dc voltages by placing a positive voltage on the $V\Omega A$ probe and ground (common) on the COM. probe. To read negative dc voltages, the leads are reversed. Polarity need not be observed in measuring ac.

When measuring dc by placing the meter in series with the circuit to be measured, the current direction must be determined beforehand. The black probe must then be placed in the more negative portion of the measured circuit.

Resistances are measured by placing a probe on each resistor lead. Polarity need not be observed when measuring resistances, as the ohmmeter portion of the multimeter uses the internal battery as the power source.

Since only one meter movement is used, the meter faceplate must have all the scales required for the various functions and ranges, as shown in Figure 24A. The single upper scale is calibrated in ohms, and is used for measuring resistances on all resistance ranges. The ohmmeter uses multipliers as does the voltmeter, and since the multipliers may be expressed in powers of 10, only one resistance scale is required. The next 3 scales — 300, 60, and 12 — are used for all dc measurements, including volts, milliamps and microamps. A similar set of scales appears below the dc scales. These are for ac volt measurements. The lowest scale is used for ac voltage measurements on the 3-volt range only.

The milliammeter, dc voltmeter, ac voltmeter and ohmmeter circuits of Figures 17, 20, 21 and 22 are combined in the multimeter circuit (Figure 24A). Placing the switch contacts of S_1 in the 300V DC position (level 1) completes a voltmeter circuit similar to the 1000V circuit of Figure 20.

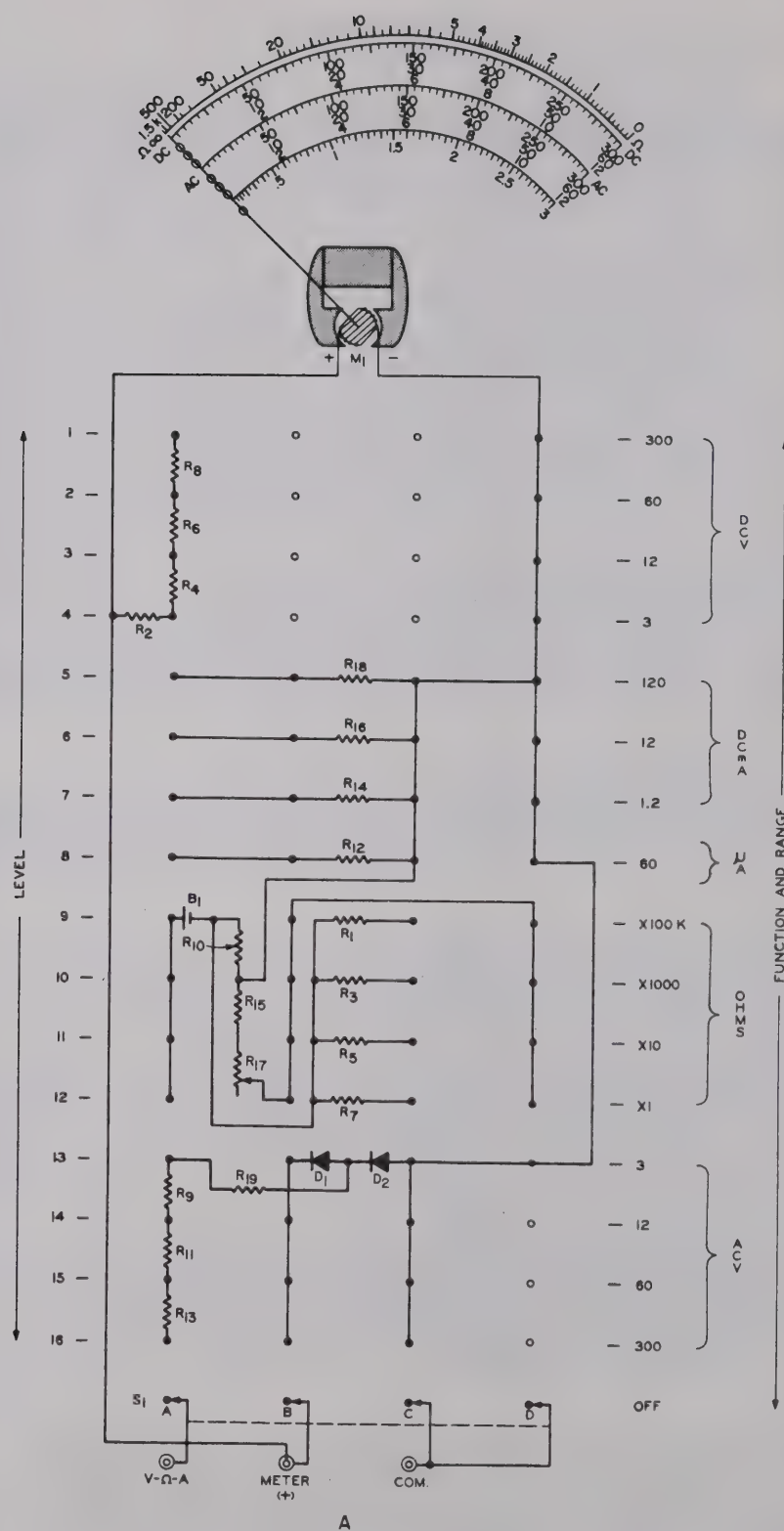
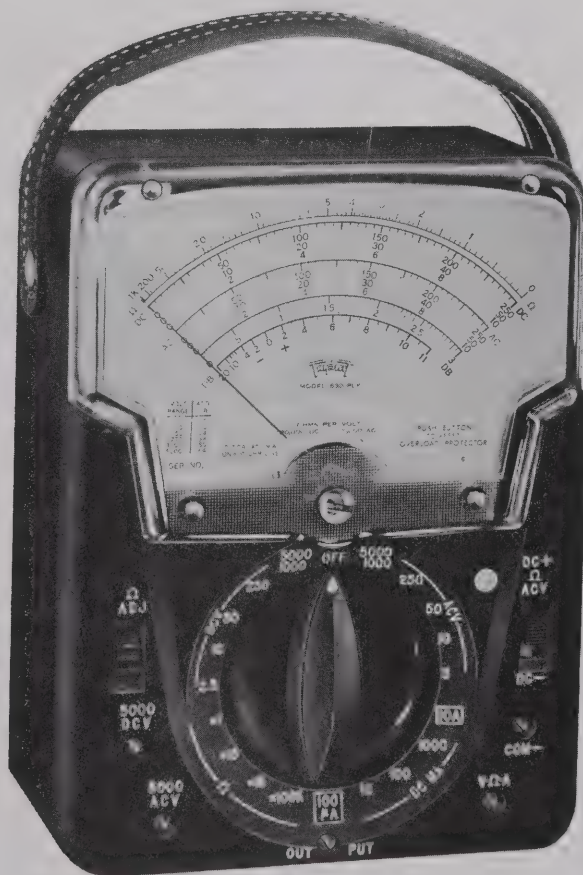


Figure 24

With the probes connected across the unknown voltage, current is drawn through the series circuit from wipers C and D of switch S_1 , through contact D-1, the moving coil M_1 , resistor R_2 , R_4 , R_6 , R_8 , wiper S_{1A} , and $V\Omega A$ terminal. This circuit has the highest series resistance obtainable with this meter, and therefore, the highest voltage reading possible.

Placing the switch contacts of S_1 on level 5, 6, 7 or 8 places a shunt resistor in parallel with M_1 permitting the multimeter to be used as a milliammeter. The milliammeter portion of Figure 24A is similar to the circuit of Figure 17. In Figure 24A, resistors R_{12} , R_{14} , R_{16} and R_{18} are the ammeter shunts. Since a low-resistance ammeter shunt permits the measurement of higher currents, R_{18} would have the lowest value and R_{12} the highest. Note that at level 5 while S_{1B} connects the positive side of the meter to R_{18} , S_{1A} and S_{1C} connect the $V\Omega A$ and COM. leads across R_{18} .



This portable multimeter uses circuitry similar to that shown in Figure 24. Most of the measurement functions and ranges can be selected with a single switch.

Courtesy Triplett Electrical Instrument Co.

Placing the S_1 switch contacts on level 9, 10, 11 or 12 permits the measurement of resistance. Figure 24B is an equivalent but simplified arrangement of level 10 of the ohmmeter section in Figure 24A. Note that although S_1 contacts A, B and C in Figure 24B are closed, no current will flow in the circuit until the unknown resistance R_X is placed in the circuit.

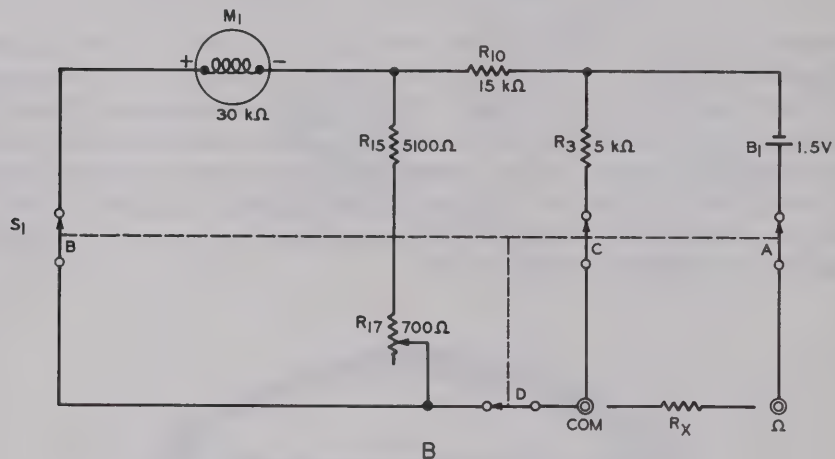


Figure 24

With the S_1 wipers at level 10 in Figure 24A, the unknown resistance is applied to one side of B_1 and R_3 . This completes a series-parallel circuit from the S_{1A} wiper (level 10), through the battery B_1 , R_{10} , M_1 , S_{1B} (level 10), S_{1D} (level 10), the COM. jack, the unknown resistor R_X , the ohms jack, and back to S_{1A} .

Placing the S_1 wipers at level 13, 14, 15 or 16 connects the meter movement and external voltages to a half-wave rectifier-type ac voltmeter circuit. With the wipers at level 16, a positive-going alternation of current appearing at the $V\Omega A$ jack permits conduction from the COM. jack, through the meter coil (negative to positive), through S_{1B} , D_1 , R_{19} , R_9 , R_{11} , R_{13} and S_{1A} . When a negative-going alternation appears at the $V\Omega A$ jack, the only current path available is from the $V\Omega A$ jack, through S_{1A} , R_{13} , R_{11} , R_9 , R_{19} , D_2 , S_{1C} , to the COM. jack, thus bypassing the meter coil. Current cannot flow through the meter circuit (from $V\Omega A$, S_{1A} , resistors R_{13} , R_{11} , R_9 , R_{19} , D_2 , M_1 and S_{1B}) because D_1 is reverse biased during a negative alternation.

WATTMETERS

Power in an electrical circuit is the rate at which energy is used and is measured in watts. Power measurements in electronics include measure-

ments of the power taken from the line, the power input and output of transmitters and the power output of amplifiers and receivers. An electrodynamic meter can be used as a **WATTMETER**, or power meter.

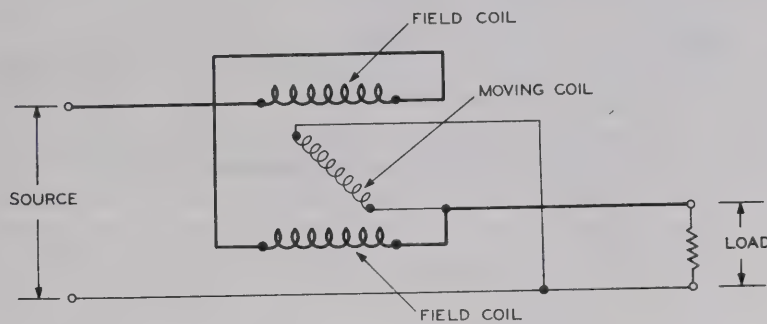


Figure 25

In actual practice, the movable coil of the wattmeter is connected across the component or device being measured, while the field coils are connected in series with it, as shown in Figure 25A. This diagram illustrates a measurement of power in some load device connected across the power line. The current through the load passes through the field coils, and a magnetic field builds up around them. The current through the movable coils depends on the voltage across the load. The magnetic fields set up by the two coils cause the movable coil to be repelled. The repulsion is directly proportional to the voltage across the load and also the current passing through the load. Thus, the meter pointer registers according to the power consumption, or the product of the voltage and the current ($E \times I$).

The electrodynamic meter movement used as a wattmeter electrically measures the power consumption of a circuit by determining the voltage across the circuit and the current through the circuit. These measurements are not completely accurate, however, since a portion of the measured power is consumed by the meter.

The power consumed by the wattmeter should be subtracted from the final wattmeter reading. The meter power can be easily checked by disconnecting the load, as shown in Figure 25B. The field coil is now in series with the movable coil. The uncompensated meter reads its own power loss. This is the correction factor which should be subtracted from the reading with the load connected. However, if the meter is compensated (has a built-in correction factor), the reading will be zero.

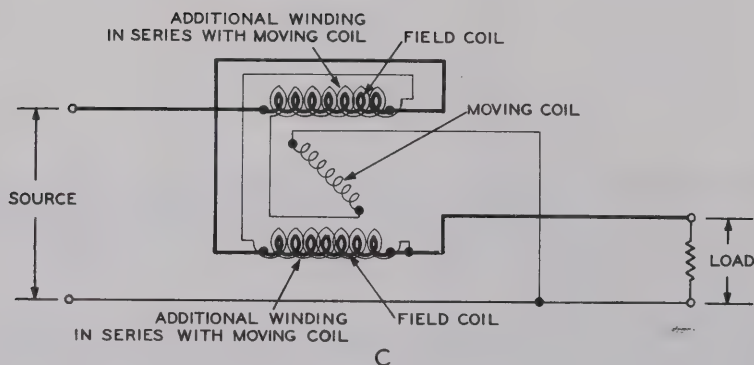
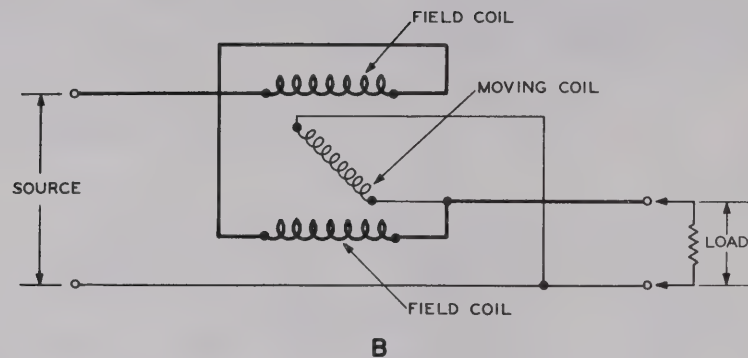


Figure 25

The greatest portion of this loss is due to the parallel connection between the load and the moving coil. Figure 25C shows a simple compensation technique for cancelling the effect of the moving-coil current. In this arrangement the field coil windings, shown in heavy lines, are the same as for the uncompensated circuit. The moving coil, however, is actually in series with two additional coils, as shown by the light lines. The extra coils of wire are wound on the field coils in the opposite direction of the original field coil windings. Since the current through the extra coils is the same as that through the moving coil, and the turns are wound electromagnetically in series opposing with the field coils, the effect of the current drawn from the load is cancelled.

Both the current and voltage coils have definite limit ratings, and overload on either one can damage the meter. For example, in a typical wattmeter designed to measure a maximum of 200 watts, the movable coil has a max-

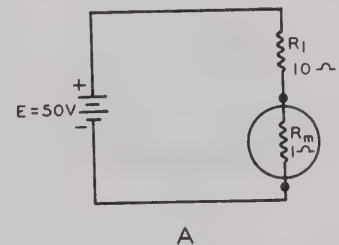
imum rating of 130 volts and the field coil has a maximum rating of 3 amperes. If either of these ratings is exceeded, overload and damage may occur.

An electrodynameometer-type wattmeter always reads true power, regardless of the power factor in the circuit. When the current is out-of-phase with the voltage, giving a power factor less than 1, maximum current does not occur at the same time as maximum voltage. Therefore, the deflection is less than it would be if the current and voltage were in phase. This effect is proportional to the amount of phase displacement between voltage and current, so that the wattmeter automatically includes the power factor in the measurement. When other types of meters are used to measure ac power, it is necessary to multiply the product of effective current and effective voltage by the power factor to calculate the true power ($P = E \times I \times pF$).

ERRORS IN USING METERS

Every meter movement has a small but definite resistance. The current through this resistance produces a small voltage across it. As a result, the meter current affects the circuit being measured and a new circuit is created when a meter is inserted.

Figure 26A shows the schematic diagram of a series circuit consisting of R_1 , R_m and Battery E. If meter resistance R_m were zero, the circuit would have the same resistance that it had before the meter was inserted. Where E is 50 volts and R_1 is 10 ohms, the current would be 50 divided by 10, or 5 amperes.



If R_m in Figure 26A is 1 ohm, the total circuit resistance increases to 11 ohms, and the circuit current is 50 divided by 11, or 4.55 amperes. Thus, the meter indicates 5 — 4.55, or .45 ampere less than the circuit normally has. This difference is the error introduced by the meter, due to its internal resistance.

A similar situation occurs when a voltmeter is used, as shown in the circuit of Figure 26B. Without the voltmeter in this circuit, the current would be the same through R_1 and R_2 , since they are in series. However, the meter draws some current, so that there is more current through R_1 than through R_2 . The increased voltage drop across R_1 because of the added current means less voltage across R_2 . This difference between the "unmetered" voltage across R_2 and the voltage across R_2 when the meter is connected is the meter error.

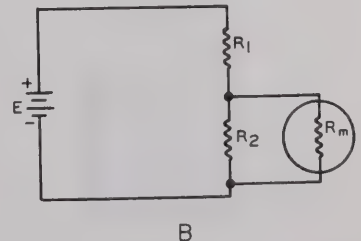


Figure
26

Meter error is usually small enough to be disregarded. In selecting meters for various measurements, it is important to remember that the less internal resistance an ammeter has, the less error it introduces. Also, the more sensitive a voltmeter is, the less current it draws, and therefore, the less error it produces. In other words, a low-resistance ammeter introduces less error when used to measure current, and a high ohms-per-volt meter introduces less error when used to measure voltage.

METER CALIBRATION

At times, it is necessary to test the accuracy or **CALIBRATION** of meter movements. The easiest and simplest way to test or calibrate a meter is to compare it with a similar meter that is known to be accurate. Figure 27 shows the arrangement for testing voltmeters and ammeters. In both instances, the square meter is assumed to be correct, and it is used to check the calibration of the round meter.

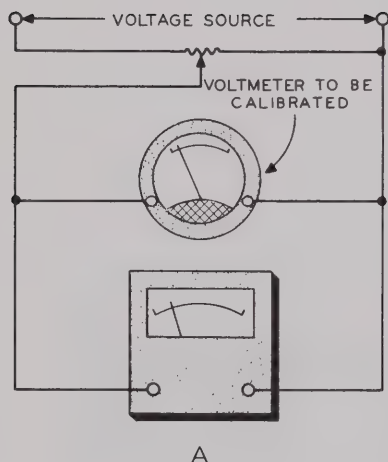


Figure 27A is the arrangement for testing voltmeters. The voltmeters are connected in parallel. This is because voltages across the branches of a parallel circuit are equal. To compare readings at different points on the scale, a high-resistance potentiometer is connected directly across the voltage source. By changing the position of the movable contact of the potentiometer, the voltage across the meters can be varied to check their readings at various points on the scale. The readings should be checked in steps from zero to full-scale deflection and then from full-scale deflection back to zero.

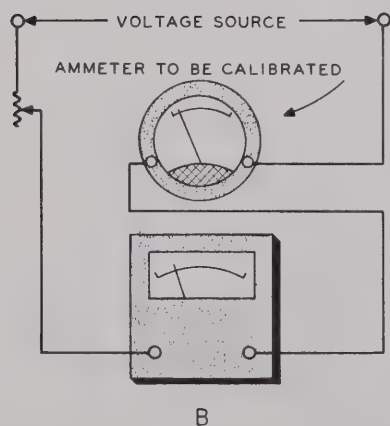


Figure
27

Figure 27B shows the arrangement for testing ammeters. The meters are now connected in series, as current is the same through a series circuit. To protect the meters, always set the rheostat at maximum resistance before connecting the circuit to a voltage source. By changing the position of the movable contact of the rheostat, the resistance of the circuit is changed. Thus, the current is varied to provide readings at various points on the meter scale. The readings should be checked in steps from zero to full-scale deflection, and then from full-scale deflection back to zero.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

DC VOLTMETERS

VOLTMETER SENSITIVITY

VOLTMETER MULTIPLIERS

RECTIFIER-TYPE AC VOLTMETERS

MULTIPLIER CALCULATIONS

OHMMETERS

MULTIMETERS

WATTMETERS

ERRORS IN USING METERS

METER CALIBRATION

26. Resistors connected in series with the moving coil in a voltmeter circuit are called _____.
27. Assume that the moving coil of Figure 20 now has a resistance of 100 ohms and requires 1 mA for full-scale deflection. What are the values of multiplier resistors R_1 and R_2 for the 10V and 100V ranges only?
28. What term is used to express voltmeter sensitivity?
29. Current through the coil of a rectifier-type ac meter produces pointer deflection which is equal to EFFECTIVE value of an alternating current. True or False?

30. In the series type ohmmeter of Figure 22, a short or zero resistance between the R_x terminals causes the pointer to deflect full scale. True or False?
31. The circuit of Figure 23 is called a _____ ohmmeter.
32. What symbol is used to indicate a resistance beyond the range of an ohmmeter?
33. A back-up ohmmeter is used mainly for measuring low resistance. True or False?
34. In the milliammeter circuit of Figure 24A, R_{16} would have a higher resistance value than R_{14} . True or False?
35. What is the function of R_{17} in Figure 24A?
36. In the meter of Figure 24A, the ohms section consists of a back-up ohmmeter. True or False?
37. When connecting a wattmeter to a circuit, how are the field coils of the wattmeter connected (in parallel or series with the load)? How is the moving-coil connected (in parallel or series with the load)?
38. A series circuit such as that of Figure 26A consists of a 100-volt battery in series with a 1000-ohm resistor, and an ammeter with a resistance of 50 ohms. What is the error, in amperes, introduced into the circuit by the meter?
39. The greater the sensitivity of a voltmeter, the less error it introduces. True or False?
40. To test or calibrate a voltmeter, it is placed in _____ with a voltmeter known to be accurate.
41. To test or calibrate an ammeter, it is placed in _____ with an ammeter known to be accurate.

SUMMARY

This lesson describes the basic types of instruments used in electrical measurements. Galvanometers are used to indicate or measure small currents in bridge circuits and other sensitive measuring circuits.

The D'Arsonval movement is used in most electronic instruments for measuring voltage and current. The moving coil is placed in the field of a permanent magnet. A direct current through the coil produces a magnetic field opposing that of the permanent magnet. The interaction of the magnetic fields causes the moving coil to rotate. The greater the field caused by the current in the coil, the greater the deflection of the pointer attached to the coil.

An ammeter is placed in series with an electrical circuit for current measurements. The ammeter must have low resistance to avoid adding an appreciable resistance to the electrical circuit. The less current required for full-scale deflection, the more sensitive the meter. The current range of the ammeter is extended by use of resistors, or shunts, connected across the terminals of the ammeter.

A voltmeter is basically a current-operated instrument. It is placed across the voltage source to measure the electric pressure. It must have high resistance to prevent any noticeable change in the circuit being tested.

The sensitivity of a voltmeter is expressed in ohms-per-volt:

$$\text{ohms-per-volt} = \frac{1}{\text{full scale current}}$$

Resistors called multipliers are connected in series with the moving coil to extend the voltage range of the meter.

Ohmmeters are used to measure resistance. Two classes of ohmmeters are the series type and the back-up type.

A multimeter combines various circuits for measuring ac or dc voltage, direct current and resistance. By use of a multiple position switch, the desired circuit can be selected.

A wattmeter indicates the amount of power in an electrical circuit. To do this, the meter measures both voltage and current, and gives a reading that is effectively the product of the two ($P = E \times I$).

Besides the D'Arsonval and electrodynamic meter movements, other meters described in this lesson can be used to measure ac or dc by modifying the meter circuit and calibrating the meter scale in terms of the desired units. The normal use of the repulsion, or moving-vane, meter is to measure ac. In electrical and radio work, thermocouple meters are used in r-f measurements.

With the information presented in this lesson, we can determine the best type of meter for a given purpose. In special cases, it is necessary to modify these basic types of meters to suit our needs.

IMPORTANT DEFINITIONS

AMMETER — An electric instrument calibrated in amperes and used for current measurements.

AVERAGE VALUE — The average of all instantaneous values of voltage or current taken for a half cycle of a sinewave. It is the product of 0.637 times the peak amplitude of the sinewave.

BACK-UP OHMMETER — An ohmmeter in which the resistance to be measured is shunted across the meter movement. Infinite resistance is at the right of the scale, corresponding to full-scale deflection. Zero resistance is at the left of the scale, corresponding to zero deflection.

CALIBRATION — A method of comparing an instrument, device or dial with a standard to determine its accuracy or to devise a scale.

CONCENTRIC-VANE MOVEMENT — A meter movement which operates on the moving-iron principle. Two concentric vanes are placed inside a moving coil and rotate with respect to each other under the force of repulsion.

DAMPING — A procedure for reducing excessive pointer swing in meter movements.

D'ARSONVAL GALVANOMETER — A type of direct current meter in which a lightweight coil of wire, supported on jewel bearings between the poles of a permanent magnet, is rotated by the effects of an electric current in the coil.

EFFECTIVE VALUE — The value of alternating current or voltage equal to the product of 0.707 times the peak amplitude. It is the electric energy equivalent of an equal amount of direct current.

ELECTRODYNAMOMETERS — Moving coil meters in which the stationary magnetic field is provided by a system of fixed coils.

ELECTROSTATIC VOLTMETERS — Voltage-sensitive devices which measure voltage directly by sensing an electrostatic charge on a system of plates in close proximity.

GALVANOMETER — A device indicating the presence of current by mechanical motion due to the magnetic effect of the current.

IMPORTANT DEFINITIONS (Continued)

GOLD LEAF ELECTROSCOPE — A sensitive indicator of the presence of an electrostatic charge.

HOT-WIRE AMMETER — A form of meter movement that functions on the principle that wire expands when it is heated by current through it and contracts when it cools. By controlling the movement of a needle by this expansion and contraction, an indication of current through the wire may be achieved.

LEFT HAND CURRENT RULE — When a wire is held in the left hand, with the thumb pointing in the direction of the electron flow, the fingers surround the wire in the same direction as the magnetic flux.

LINEAR SCALE — A scale on which corresponding divisions are of equal size.

METER MOVEMENT — That part of an electric meter in which electric energy is converted to mechanical energy.

MICROAMMETER — An electric instrument calibrated in microamperes (millionths of 1 amp) designed to accurately measure currents less than 1 amp.

MILLIAMMETER — An electric instrument calibrated in milliamperes (thousandths of 1 amp) designed to accurately measure currents less than 1 amp.

MOVING-IRON METERS — Meter system operating on the principle that an electromagnet magnetizes soft iron.

MULTIMETER (VOM) — A single device that combines the function of an ammeter, voltmeter and ohmmeter. It is also called a VOM.

MULTIPLIER — A resistor connected in series with the meter movement to increase the range of a voltmeter.

NONLINEAR SCALE — A meter scale, the divisions of which are crowded at one end and farther apart at the other end.

OHMMETER — An electric instrument calibrated in ohms and used for resistance measurements.

IMPORTANT DEFINITIONS (Continued)

PERMANENT-MAGNET MOVING-COIL (PMMC) — A general class of meter mechanism based on the D'Arsonval movement principles.

RADIAL-VANE MOVEMENT — A meter movement which operates on the moving-iron principle. Two rectangular vanes, extending radially from each other, are placed inside a stationary coil, and are caused to move apart from the effect of magnetic repulsion.

SENSITIVITY — Pertaining to meters, sensitivity is a measure of the current required for full-scale deflection. For a voltmeter it is expressed in ohms-per-volt.

SERIES OHMMETER — An ohmmeter in which the resistance to be measured is placed in series with the meter movement and the ohmmeter voltage source. Infinite resistance is at the left of the meter scale, corresponding to zero deflection. Zero resistance is at the right of the scale, corresponding to the full-scale deflection.

SHUNT — A resistor connected in parallel with the meter movement to increase the range of the current meter.

SQUARE LAW SCALE — See NONLINEAR SCALE.

TAUT BAND — A meter movement suspension system having very low friction characteristics.

THERMOCOUPLE — A pair of dissimilar metals forming a junction at which a voltage is generated when heat is applied.

THERMOCOUPLE AMMETER — An ammeter which is actuated by a voltage generated in a thermocouple which is heated by the current flowing in a wire.

VOLTMETER — An electric instrument calibrated in volts and used for voltage measurements.

WATTMETER — An electric instrument calibrated directly in watts and used for power measurements.

PRACTICE EXERCISE SOLUTIONS

1. The Left Hand Current Rule.
2. True
3. (c) current.
4. external magnet D'Arsonval — This type of meter depends on the reaction between the magnetic field around a direct current carrying coil and a stationary magnetic field for its operation.
5. True — Not only does the hairspring hold the pointer at the zero position for zero current in the coil, it also serves to connect the external circuit to the moving coil and to return the pointer to zero after a reading is made.
6. False — The coil movement depends on the attraction and repulsion of the coil poles by the permanent magnet poles. Reversing the current through the coil reverses the magnetic polarity of the coil field, and thus causes the coil and attached pointer to move in the opposite direction.
7. Electrodynamic.
8. (c) both ac and dc. — When the direction of current through the meter coil is reversed, the magnetic polarity of both the fixed and movable coils is reversed, so that the turning force remains in the same direction.
9. (b) electrostatic.
10. False — The electroscope has no calibrated dial, and no qualitative measurement is possible.
11. False — The attraction and repulsion required to operate an electrostatic meter is INVERSELY proportional to the distance between the plates.
12. plunger; repulsion
13. (b) moving-vane meters — Moving-vane meters register according to the square law, while moving-coil meters register directly proportional to the amount of current flow in the moving coil.

PRACTICE EXERCISE SOLUTIONS (Continued)

14. Heat — Hot-wire ammeters use the heat generated by current flow in a current-carrying wire to expand the wire, thus allowing the pointer to move.
15. False — The thermocouple meter measures both ac and dc. However, the output of the thermocouple device is dc, which is applied to a moving-coil meter movement.
16. The purpose of suspension systems is to support the moving coil and allow the moving coil to turn freely on its axis.
17. True — The springs absorb the shock from rough handling.
18. (b) less.
19. True — Damping slows down the pointer as it approaches the desired reading and as it returns to zero.
20. air-vane; electromagnetic
21. False — The coil resistance must be low to prevent any appreciable decrease in circuit current because the ammeter is placed in series with the current it measures.
22. (b) less sensitivity. — The less current an ammeter movement draws for full-scale deflection, the more sensitive the ammeter is.
23. 10 mA. — This current is also the sensitivity of the ammeter.
24. $R_1 = 11.11$; $R_2 = 1.01$ ohms. — With the switch set to the 10 mA range, resistor R_1 is connected across the moving coil. By Ohm's Law ($E = IR$), the voltage across the moving coil for full-scale deflection is $.001 \times 100 = .1$ volt. R_1 must carry 9 mA (.009 ampere) for full-scale deflection when the meter is switched to the 10 mA range. With .1 volt across R_1 , and a current of .009 ampere through the resistor, the resistance value is:

$$R_1 = \frac{E}{I} = \frac{.1}{.009} = 11.11 \text{ ohms.}$$

PRACTICE EXERCISE SOLUTIONS (Continued)

For the 100 mA range, R_2 is connected across the meter coil. This resistor must carry 99 mA (.099 ampere) with a voltage of .1 volt applied. By Ohm's Law:

$$R_2 = \frac{.1}{.099} = 1.01 \text{ ohms.}$$

25. False — Shunts can only be used to increase the maximum range of an ammeter.
26. multipliers — These resistors prevent the current in the meter circuit from exceeding the full-scale value of the moving coil when the meter is connected across the voltage source.
27. $R_1 = 9900$ ohms; $R_2 = 90,000$ ohms. — For the 10V range, the total resistance consists of the coil resistance and R_1 in series. With 10 volts applied to this series circuit, the resistance required to limit the meter current to a full-scale value of 1 mA (.001 ampere) is:

$$R_T = \frac{E}{I} = \frac{10}{.001} = 10,000.$$

The coil provides 100 ohms of this total, so multiplier R_1 must have a value of 10,000 — 100, or 9900 ohms.

For the 100V range, the total resistance is that of R_1 , R_2 and the coil in series. With 100 volts applied, the resistance required to limit the current to 1 mA is:

$$R_T = \frac{E}{I} = \frac{100}{.001} = 100,000 \text{ ohms.}$$

The coil and R_1 provide 10,000 ohms of the total. Multiplier R_2 must provide 100,000 ohms — 10,000 ohms, or 90,000 ohms.

28. Ohms-Per-Volt.
29. False — Current through the coil produces pointer deflection equal to the AVERAGE value.
30. True

PRACTICE EXERCISE SOLUTIONS (Continued)

31. back-up — The back-up ohmmeter receives its name from the fact that when resistance is measured, the pointer moves in a direction backward to that of the series-type ohmmeter.
32. ∞ (infinity).
33. True
34. False — In order to measure 12 mA as opposed to 1.2 mA, R_{16} would have a lower resistance value than R_{14} .
35. The Ohms Adjust control.
36. False — The ohms scale is that of a series-type meter.
37. The field coils are in series with the load, and the moving coil is in parallel with the load.
38. .0048 ampere (approximately). — With no meter in the circuit, the current is:

$$I = \frac{E}{R_1} = \frac{100}{1000} = .1 \text{ ampere.}$$

When the meter resistance of 50 ohms is added to the circuit, the resistance increases to $1000 + 50$, or 1050 ohms, and the current is:

$$I = \frac{E}{R_1 + R_m} = \frac{100}{1050} = .0952 \text{ ampere (approximately).}$$

The meter error is the difference between the two values:

$$.1 - .0952 = .0048 \text{ ampere.}$$

39. True — The voltmeter is basically a current-operated device. The less current it takes to move the coil, the more sensitive the meter is.
40. parallel
41. series



1055A

1055A
EXAMINATION
CHECK SHEET

1. B - WHEN BROUGHT NEAR A CURRENT-CARRYING CONDUCTOR, A COMPASS NEEDLE -- TENDS TO ALIGN ITSELF PARALLEL TO THE ELECTROMAGNETIC FIELD.

The direction of the electromagnetic field generated by a current-carrying conductor is at right angles to the wire, and since the compass needle also points at right angles to the wire, the electromagnetic field and the compass needle are parallel.

2. D - THE MOST WIDELY KNOWN METER MOVEMENT THAT USES THE PERMANENT MAGNET MOVING COIL MECHANISM IS THE -- D'ARSONVAL GALVANOMETER.

D'Arsonval patented a moving coil mechanism in 1881 from which evolved other types of PMMC devices.

3. C - THE ELECTRODYNAMIC MOVEMENT OPERATES ON THE PRINCIPLES OF -- THE INTERACTION BETWEEN ELECTROMAGNETIC FIELDS.

Field coil windings are used with a moving coil mechanism, and the field forces generated are entirely electro-magnetic.

4. A - MODERN INSTRUMENTS USING TAUT BAND SUSPENSION SYSTEMS -- CAN BE MADE WITH HIGHER SENSITIVITIES THAN THOSE USING PIVOTS AND JEWELS.

The taut band suspension reduces the already low friction levels of pivot and jewel movements.

5. D - AMMETER SHUNTS -- GENERALLY HAVE A LOW RESISTANCE VALUE.

The shunt resistor is placed in parallel with the moving coil and in order to draw the proper amount of current, must have a resistance value lower than that of the coil.

6. D - A TECHNICIAN DESIRES TO MEASURE THE CURRENT IN A CIRCUIT WHICH HE KNOWS IS GREATER THAN 1 AMPERE, BUT LESS THAN 3 AMPERES. THE ONLY AVAILABLE METER, HOWEVER, HAS A SENSITIVITY OF 250 mA. WITH A COIL RESISTANCE OF 50 OHMS, THE VALUE OF THE SHUNT RESISTOR REQUIRED IS APPROXIMATELY -- 4.5 OHMS.

Meter sensitivity is defined as the amount of current required for full-scale deflection. Since the meter movement can carry no more than this, the remainder of the current must be shunted away from the coil.

Thus,

3.00 amperes is the maximum amount of current in the circuit
-0.25 amperes is the maximum amount of current in the coil
therefore 2.75 amperes must be carried by the shunt resistor.

Since the current and resistance of the coil are known for the required condition, the voltage across the coil can be determined $E = IR$, $E = .250 \times 50$, $E = 12.5V$.

The coil and shunt resistor are in parallel, therefore the voltage across the resistor is also 12.5V. Solving for the resistance:

$$R = \frac{E}{I} = \frac{12.5}{2.75} = 4.5\Omega.$$

7. D - ASSUME THAT THE RESISTANCE OF THE MOVING COIL IN FIGURE 18 IS 1K OHM, AND THE METER NEEDLE IS INDICATING 100 VOLTS. IF R_1 IS 50,000 OHMS, THE SENSITIVITY OF THE VOLTMETER IS -- 510 OHMS PER VOLT.

The total resistance of the circuit is 51,000 ohms. Since the meter is indicating 100 volts, this is the voltage across the circuit. Thus $51,000 \div 100 = 510$ ohms per volt.

1055A

QUESTIONS

IMPORTANT — These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
1055A

Example: A hammer is a type of

A	
B	
C	
D	

A. food. B. bird. C. tool. D. cart.

1. A ☐ B ☒ C ☐ D ☐ **When brought near a current-carrying conductor, a compass needle**
(A) tends to point in the direction of the current flow. (B) tends to align itself parallel to the electro-magnetic field. (C) measures the amount of voltage in the circuit. (D) tends to align itself parallel to the wire.
2. A ☐ B ☐ C ☐ D ☒ **The most widely known movement that uses the Permanent-Magnet Moving-Coil mechanism is the**
(A) Kelvin Astatic galvanometer. (B) electrostatic voltmeter. (C) electro-dynamometer. (D) D'Arsonval galvanometer.
3. A ☐ B ☐ C ☒ D ☐ **The electrodynamic movement operates on the principles of**
(A) the interaction between magnetic and electromagnetic fields. (B) the interaction between voltages of the opposite polarity. (C) the interaction between electromagnetic fields. (D) the interaction between a coil and a soft iron bar.
4. A ☒ B ☐ C ☐ D ☐ **Modern instruments using taut-band suspension systems**
(A) can be made with higher sensitivities than those using pivots and jewels. (B) are easily damaged by shock and cannot be used in some applications presently served by pivoted instruments. (C) can be used only in the upright position. (D) are widely used in the electrostatic voltmeter.
5. A ☐ B ☐ C ☐ D ☒ **Ammeter shunts**
(A) limit excessive currents through the coil by increasing the resistance in the coil circuit. (B) permit a voltmeter to be used as an ammeter. (C) are used to decrease the range of the meter. (D) generally have a low-resistance value.
6. A ☐ B ☐ C ☐ D ☒ **A technician desires to measure the current in a circuit which he knows is greater than 1 ampere, but less than 3 amperes. The only available meter, however, has a sensitivity of 250 mA. With a coil resistance of 50 ohms, the value of the shunt resistor required is approximately**
(A) .045 ohm. (B) .1 ohm. (C) 10.6 ohms. (D) 4.5 ohms.
7. A ☐ B ☐ C ☐ D ☒ **Assume that the resistance of the moving coil in Figure 18 is 1 k Ω , and the meter needle is indicating 100 volts. If R_1 is 50,000 ohms, the sensitivity of the voltmeter is**
(A) 1000 ohms-per-volt. (B) 1050 ohms-per-volt. (C) 500 ohms-per-volt. (D) 510 ohms-per-volt.
8. A ☐ B ☒ C ☐ D ☐ **Using Figure 24A, assume that selector switch S_1 is positioned on the ohms $\times 1000$ range, and the pointer on the meter movement indicates a reading of 10. Given the component values shown in Figure 24B, and R_{17} set at 700 ohms, the current through R_x is approximately**
(A) .3 mA. (B) .1 mA. (C) .15 mA. (D) .3A.
9. A ☐ B ☐ C ☐ D ☒ **Reversing the leads when measuring ac with the circuit in Figure 24A would**
(A) cause current to flow in the opposite direction through the meter. (B) cause the diodes to block all current to the meter. (C) cause the meter needle to oscillate or vibrate around the zero marking. (D) have no effect on the reading.
10. A ☐ B ☒ C ☐ D ☐ **In CONCENTRIC MOVING-VANE meters, the pointer indicates**
(A) in direct proportion to the amount of current flow. (B) according to the square law. (C) using a linear scale. (D) the same as the D'Arsonval movement.

EXPERIMENT 5

TRANSISTOR CIRCUITS—COMMON—EMITTER AND COMMON—COLLECTOR AMPLIFIERS

PARTS NEEDED

- | | |
|--|--------------------------------------|
| 1 - Multimeter with Test Leads and Spring Adapters | 1 - 1 k Ω , 1/2 W, Resistor |
| 1 - Partially Completed Design Console | 1 - 4.7 k Ω , 1/2 W, Resistor |
| 1 - NPN Transistor | 2 - 10 k Ω , 1/2 W, Resistors |
| 1 - PNP Transistor | 1 - 22 k Ω , 1/2 W, Resistor |
| 11 - Modular Connectors | 1 - 100 k Ω , 1/2 W, Resistor |
| 1 - Transistor Socket with Leads | 1 - 220 k Ω , 1/2 W, Resistor |
| 1 - 470 Ω , 1/2 W, Resistor | 1 - 1 M Ω , 1/2 W, Resistor |
| | - Hookup Wire |

OBJECTIVE

By working with the circuits in this experiment, you will gain familiarity with the dc operating conditions of the common-emitter amplifier and common-collector transistor amplifier circuits. Both PNP and NPN circuits will be constructed with the similarities and differences pointed out.

In reviewing the basic operating requirements for transistors as amplifiers, the base-to-emitter junction must be forward biased while the base-to-collector junction must be reverse biased. The circuits constructed in these experiments will employ the conventional single supply biasing technique. A stabilizing arrangement is used so that the circuits will operate with a wide variation in transistor characteristics. You might wish to review your lesson material on biasing techniques while you work through this experiment.

PART 1

PROCEDURE

NPN COMMON-EMITTER AMPLIFIER

1. Figure 5-1 shows a common-emitter transistor amplifier circuit employing an NPN silicon transistor. Construct the circuit of Figure 5-1 on your design console, following the layout of Figure 5-2. (This includes the insertion of the NPN silicon transistor.) Refer back to Experiment 1 for the information on transistor connections. Be especially careful that you make the proper connections to the modular connectors that supply the output voltage from the design console power supply. Make sure that the design console power supply is turned off while you are constructing the circuit.

2. Set up your multimeter to measure dc voltage, and connect the test leads to

Transistor Circuits - Common-Emitter and Common-Collector Amplifiers

the + and - terminals of the REGULATED LOW VOLTAGE supply to measure the variable low voltage dc power supply output. Set the Voltage Adjust control fully counterclockwise. Turn on the design console by setting the switch to the 30V position.

3. Rotate the Voltage Adjust control clockwise until the power supply output voltage is 15 volts.

4. Measure the dc voltages at the emitter, base and collector of Q_1 with respect to GND (ground), and record in the space provided below.

Emitter 0 volts dc
Base .7 volts dc
Collector 8 volts dc

The actual voltages measured will depend upon the beta (or current gain) of the transistor. However, you should obtain a difference of approximately 0.6 volt between the base and emitter voltage. This is the normal forward biased junction voltage for a SILICON transistor. For example, if the voltage at the emitter is 0.1 volt, the voltage at the base should be approximately 0.7 volt.

The circuit values have been chosen so the collector voltage will be about half the supply voltage, approximately 7 volts. By using the stabilizing arrangement shown in Figure 5-1 (the bias resistor R_2 is connected to the collector and the unbypassed resistor, R_4 , is connected to the emitter), the dc operating characteristics will not vary widely with changes in transistor beta.

5. Even though a stabilizing arrangement is employed in the circuit of Figure 5-1, the dc operating conditions will still vary with changes in the value of bias. (Remember, bias determines the base current.) To show the effects of a change in bias, connect a 220 k Ω , 1/2 W, resistor in parallel with R_2 . Turn off the design console while making this change. This lowers the effective value of R_2 , and increases the value of base current. Turn on the design console. Measure the voltages at the emitter, base and collector (with respect to ground) and record the values below. Make sure that the supply voltage is still set at 15 volts.

Emitter 0.1 volts dc
Base 0.8 volts dc
Collector 6 volts dc

With an increase in base current, you should observe a slight increase in the voltages at the emitter and at the base. However, the difference between the

Transistor Circuits - Common-Emitter and Common-Collector Amplifiers

voltages at the base and emitter will still be 0.6 volt. The base-to-emitter junction voltage remains somewhat constant, even though the current changes.

The collector voltage will decrease, since the increase in base current causes an increase in collector current.

6. Now, let's examine the effects of reducing the base-to-emitter voltage to zero. This should cut off the transistor. Turn off the design console. First remove the 220 k Ω resistor that was connected across the 100 k Ω bias resistor R_2 in Figure 5-1, as well as the 100 k Ω resistor, R_2 . Next connect a jumper wire from the base to the emitter of the transistor. Turn on the design console, and reset the power supply output to 15 volts.

7. Measure the emitter, base and collector voltages of the transistor and record them below.

Emitter	<u>0</u>	volts dc
Base	<u>0</u>	volts dc
Collector	<u>15</u>	volts dc

With the bias resistor removed and the base-to-emitter junction shorted, you should obtain 0 volts at the base and at the emitter. This cuts off the transistor and, with no collector current, the collector voltage will be approximately equal to the supply voltage. Since there is some leakage current, a small voltage drop will occur across the collector load resistor R_1 , and the collector voltage will be slightly less than the supply voltage, about 0.5 volt or less.

PART 2

PROCEDURE

NPN COMMON-COLLECTOR AMPLIFIER

1. Figure 5-3 shows the schematic diagram of an NPN common-collector amplifier, often called an "emitter follower." Set up the circuit on your design console, following the layout of Figure 5-4. This includes inserting the transistor. Be sure to turn off the design console while constructing or changing the circuit.

2. Turn on the design console, and again set the supply voltage to 15 volts. Measure the voltages at the emitter, base and collector and record below.

Transistor Circuits - Common-Emitter and Common-Collector Amplifiers

Emitter 3.6 volts dc
Base 4.2 volts dc
Collector 15 volts dc

Note that, in the emitter follower circuit, the collector voltage is equal to the supply voltage. The base voltage will again be approximately 0.6 volt higher than the emitter voltage.

3. Let's examine the effects of an increase in bias. Turn off the design console and remove the 22 k Ω bias resistor, R₁. Replace it with a 10 k Ω resistor. Turn on the design console and remeasure the voltages at the emitter, base and collector and record below. Make sure that the power supply output voltage is still 15 volts.

Emitter 6.9 volts dc
Base 7.4 volts dc
Collector 15 volts dc

Compare your readings to those obtained in Step 2. Note that the emitter voltage is higher, due to the increased collector current when R₁ is reduced to 10 k Ω . Note that the collector voltage remains unchanged in this circuit, since it is tied directly to the power supply. Again the base voltage is approximately 0.6 volt higher than the emitter voltage. Turn off the design console.

PART 3

PROCEDURE

PNP COMMON-EMITTER AMPLIFIER

1. Figure 5-5 shows the circuit of a common-emitter amplifier employing a germanium PNP transistor. The only differences between this circuit and the NPN circuit of Figure 5-1 are the transistor, the polarity of the supply voltage and the values of the bias resistors. Set up the circuit of Figure 5-5 using your PNP transistor. You can use the layout of Figure 5-2 as a guide, but be sure to reverse the power supply connections and use the proper values for R₂ and R₃.

2. Turn on the design console, and set the power supply to 15 volts. In the PNP circuit the + power supply terminal is the ground (or reference point), as shown in Figure 5-5. Measure the voltages at the emitter, base and collector with respect to ground (GND) and record below. Note: All readings should be shown as negative.

Transistor Circuits - Common-Emitter and Common-Collector Amplifiers

Emitter - 0.1 volts dc
Base - 0.2 volts dc
Collector - 8.7 volts dc

Compare the measurements in the PNP circuit to those obtained in Step 4 of the Procedure, Part 1 for the NPN circuit. In addition to the voltages being negative, you will note that the difference between the base and emitter voltage is much less than 0.6 volt, actually approximately 0.2 to 0.3 volt. This lower base-emitter voltage is characteristic of a GERMANIUM transistor.

3. A PNP circuit functions similar to an NPN circuit when the supply voltage polarity is changed. Let's increase the bias by connecting a 1 M Ω resistor in parallel with the 220 k Ω resistor, R₂. Turn off the design console while you make the change.

4. Turn on the design console, and make sure the power supply is set to 15 volts. Measure the voltages at the emitter, base and collector and record below.

Emitter - 0.1 volts dc
Base - 0.2 volts dc
Collector - 8.2 volts dc

With an increase in base current, the voltage at the emitter should increase and likewise the voltage at the base will increase. On the other hand, the voltage at the collector will decrease, since the increased collector current causes an increase in the voltage drop across the collector load resistor R₁.

5. Turn off the design console, and remove the 1 M Ω resistor connected across R₂. To examine the effects of zero bias, connect a jumper between the base and the emitter of Q₁. Turn on the design console and make sure the power supply output is 15 volts. Measure the voltages at the emitter, base and collector. Record them below.

Emitter 0 volts dc
Base 0 volts dc
Collector - 13 volts dc

With the base-to-emitter junction shorted, the transistor is cut off. As a result, the base and emitter voltages will be approximately zero, and the collector voltage will equal the supply voltage. Any slight difference between

Transistor Circuits - Common-Emitter and Common-Collector Amplifiers

the collector and the supply voltage is due to the small leakage current flowing through the collector load resistor R_1 .

PART 4

PROCEDURE

PNP COMMON-COLLECTOR AMPLIFIER

1. Turn off the design console, and set up the PNP common-collector amplifier circuit of Figure 5-6. You can follow the layout shown for the NPN circuit in Figure 5-4. MAKE SURE THAT YOU REVERSE THE POWER SUPPLY CONNECTIONS FROM THOSE SHOWN IN FIGURE 5-4. R_1 is a $10\text{ k}\Omega$ resistor in the new circuit.

2. Turn on the design console, and make sure the power supply is set to 15 volts. Measure the voltages at the emitter, base and collector and record below.

Emitter -7.1 volts dc

Base -7.2 volts dc

Collector -15 volts dc

Your readings should be similar to those for the NPN circuit, Procedure, Part 2, Step 2, except for the reverse polarity and the lower base-to-emitter voltage of the germanium transistor.

3. To show the effects of increased bias, connect a $22\text{ k}\Omega$ resistor across the $10\text{ k}\Omega$ bias resistor, R_1 . Turn off the design console while making the change. Turn on the design console and check that the power supply output is 15 volts. Record the element voltages below. Then, turn off the design console.

Emitter -8.4 volts dc

Base -8.4 volts dc

Collector -15 volts dc

4. To examine the effects of zero bias, remove the added $22\text{ k}\Omega$ resistor, and connect a jumper between the base and emitter of Q_1 . Turn on the design console and make sure that the power supply output is 15 volts. Record the element voltages below. Turn off the design console.

Emitter -1.3 volts dc

Base -1.3 volts dc

Collector -15 volts dc

Transistor Circuits - Common-Emitter and Common-Collector Amplifiers

In Step 3 when the bias is increased, you should have observed an increase in the emitter and base voltages, due to an increase in collector current. When the bias was reduced to zero in Step 4, the opposite action occurred. The voltages at the emitter and the base decreased, because of the decrease in collector current. The small leakage current flowing accounts for the low voltages at the emitter and base. The collector voltage remains constant since the collector is connected directly to the supply.

CONCLUSION

In this experiment you examined the dc operating conditions for NPN and PNP common-emitter and common-collector transistor amplifier circuits. For silicon transistors, the normal base-to-emitter voltage is approximately 0.6 volt, while for germanium transistors it is between 0.2 and 0.3 volt.

When the bias on a transistor is increased, the collector current increases. In a common-emitter stage with an emitter resistor, this causes an increase in voltage at the emitter and a decrease in voltage at the collector. On the other hand, when the bias is decreased, the opposite occurs: emitter voltage decreases and collector voltage increases. The action is similar in a common-collector (or emitter follower) stage with the exception that the voltage at the collector remains constant.

The circuit action for PNP and NPN transistors is the same. Only the polarity of the source and element voltages differs. In an NPN circuit, the base and collector are positive with respect to the emitter. With a PNP circuit, the base and collector are negative with respect to the emitter.

NOTES

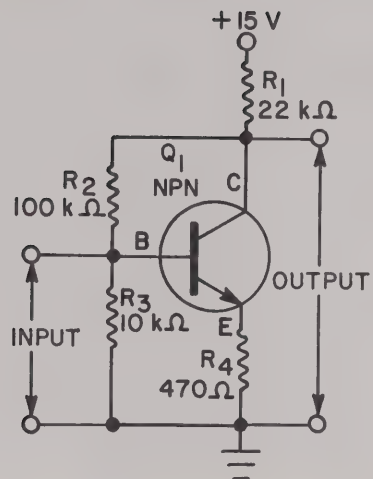


FIGURE 5-1

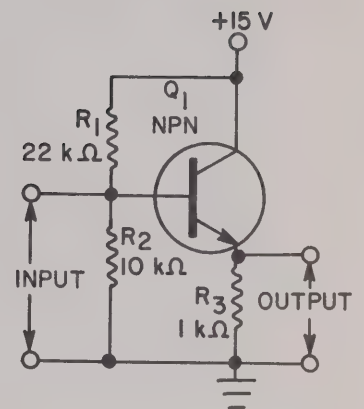


FIGURE 5-3

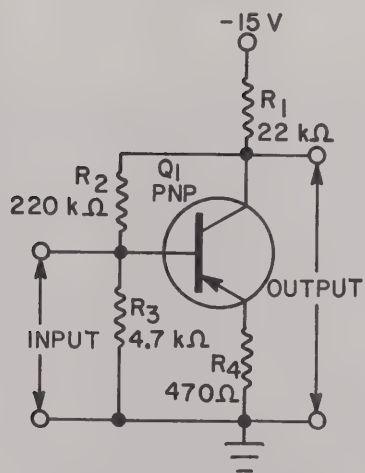


FIGURE 5-5

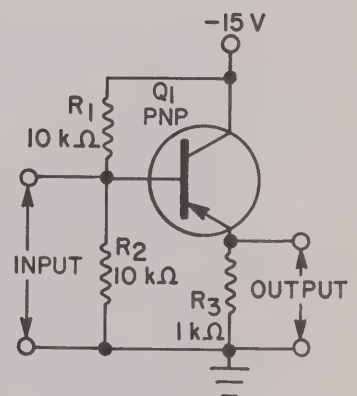


FIGURE 5-6

NOTES

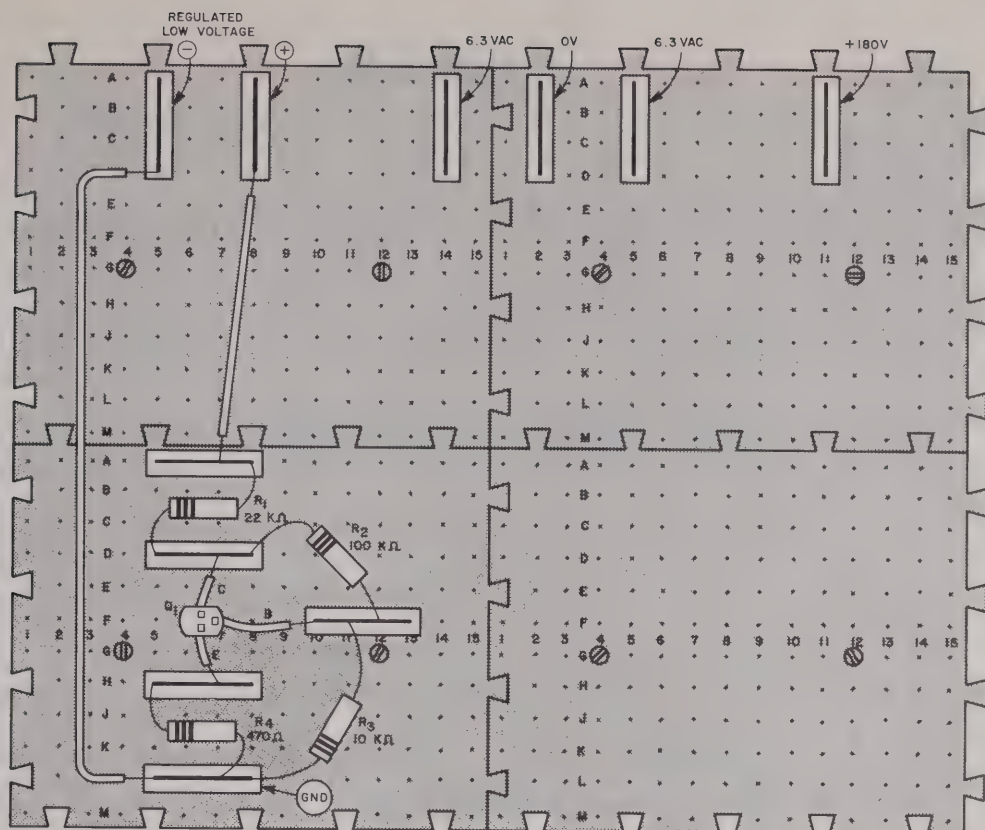


FIGURE 5-2

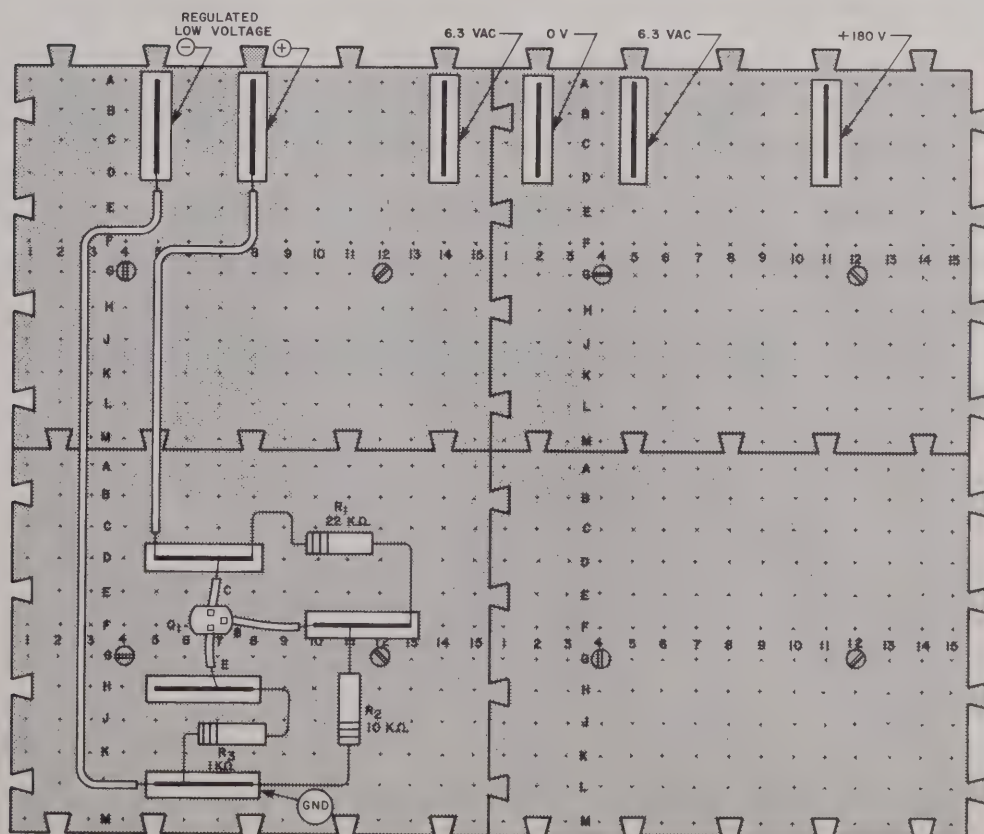


FIGURE 5-4

NOTES



ONE OF THE

BELL & HOWELL SCHOOLS

9504-5A
EXAMINATION
CHECK SHEET

1. D - THE NORMAL VOLTAGE DROP ACROSS A FORWARD BIASED SILICON PN JUNCTION IS APPROXIMATELY -- 0.6 VOLT.

For a silicon transistor, the normal forward biased base-to-emitter junction bias is approximately 0.6 volt.

2. B - UNDER WHICH OF THE FOLLOWING CONDITIONS IS THE BASE-TO-EMITTER JUNCTION OF AN NPN SILICON TRANSISTOR FORWARD BIASED? -- EMITTER AT -5 VOLTS, BASE AT -4.4 VOLTS.
To forward bias an NPN transistor, the base must be 0.6 volt more positive (or less negative) than the emitter.

3. B - REFERRING TO THE CIRCUIT OF FIGURE 5-1, IF BASE CURRENT INCREASES, -- THE VOLTAGE AT THE COLLECTOR DECREASES.

When base current increases, collector current increases, increasing the voltage drop across the collector load resistor R_1 . This causes a reduction in the collector voltage.

4. D - REFERRING TO THE CIRCUIT OF FIGURE 5-3, THE VOLTAGE AT THE COLLECTOR -- DOES NOT VARY.

In the common-collector circuit, the collector is connected to the supply and thus does not vary when the collector current changes.

5. A - WHEN A JUMPER IS CONNECTED FROM THE BASE TO THE EMITTER OF Q_1 IN THE CIRCUIT OF FIGURE 5-5, -- THE VOLTAGE AT THE COLLECTOR BECOMES MORE NEGATIVE.

With the jumper in place, the transistor is cut off reducing collector current and increasing collector voltage.

6. B - WHEN A RESISTOR IS CONNECTED IN PARALLEL WITH THE BIAS RESISTOR R_2 IN FIGURE 5-5, -- THE VOLTAGE AT THE EMITTER INCREASES.

The additional resistor increases base current thus increasing the emitter voltage.

7. C - WITH REGARD TO NORMAL TRANSISTOR ACTION, -- COLLECTOR CURRENT IS PROPORTIONAL TO BASE CURRENT.

The ratio of base current to collector current is the current gain or beta of the transistor.

8. D - WHEN THE BASE OF Q_1 IS SHORTED TO THE EMITTER IN THE CIRCUIT OF FIGURE 5-3, THE -- VOLTAGE AT THE EMITTER DECREASES.

Shorting the base to the emitter cuts off the transistor, decreasing collector current and thus bringing the emitter voltage to zero.

9. C - THE NORMAL VOLTAGE DROP ACROSS A FORWARD BIASED GERMANIUM PN JUNCTION IS APPROXIMATELY -- 0.2 VOLT.

The normal forward biased emitter junction voltage for a germanium transistor is less than that for a silicon, about 0.2 to 0.3 volt.

10. C - UNDER WHICH OF THE FOLLOWING CONDITIONS IS THE BASE-TO-EMITTER JUNCTION OF A GERMANIUM PNP TRANSISTOR REVERSE BIASED? -- EMITTER AT -3 VOLTS, BASE AT -2.5 VOLTS.

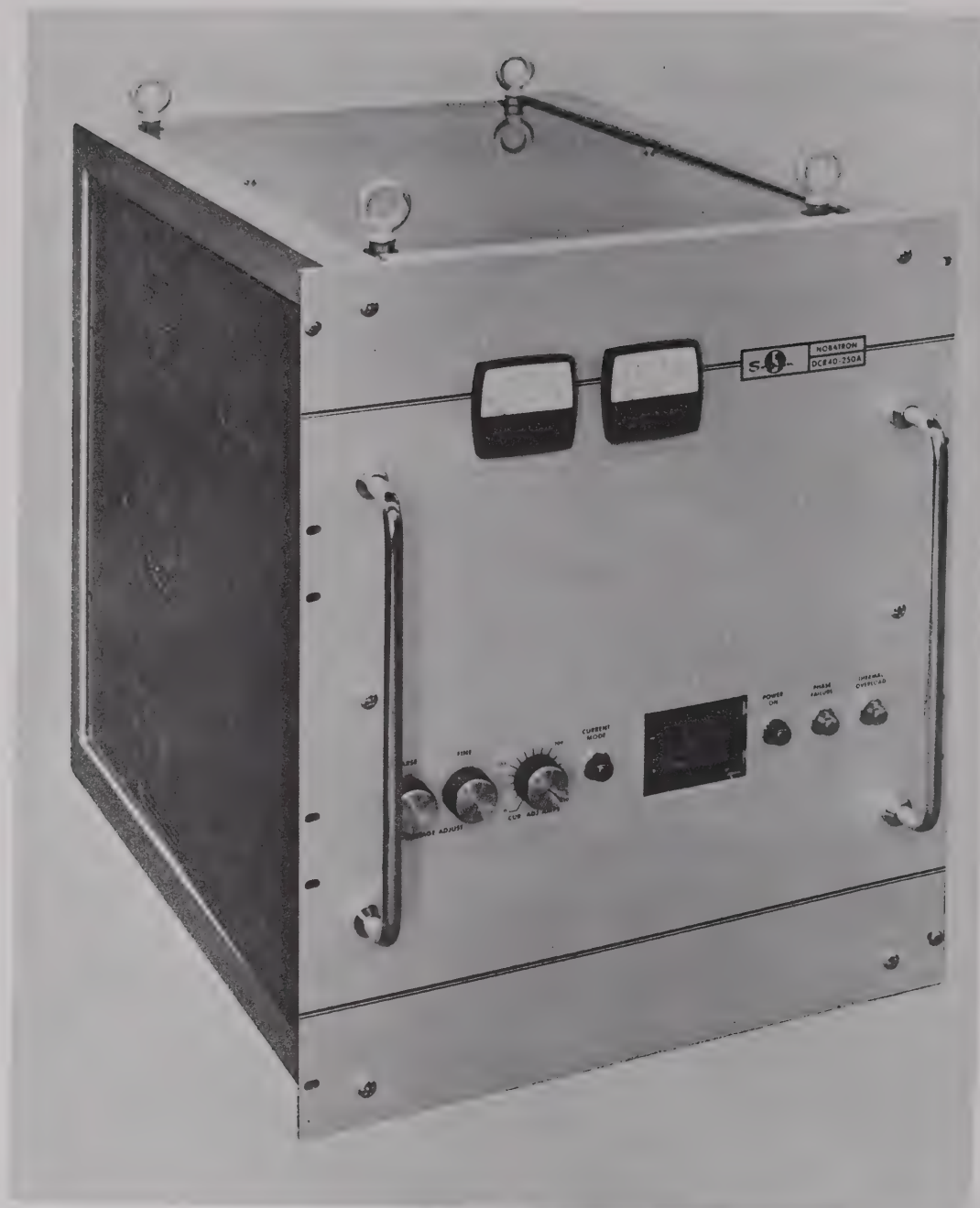
To reverse bias a PNP transistor, the base must be more positive (or less negative) than the emitter.

USING VECTORS

1058

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Phase shift circuits are used in conjunction with silicon controlled rectifiers in the above power supply to provide an adjustable and regulated output voltage.

Courtesy Raytheon Co., Sorensen Operation

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Knowledge once gained casts a faint light beyond its own immediate boundaries. There is no discovery so limited as not to illuminate something beyond itself.

—John Tyndall

USING VECTORS

The ability of scientists and engineers to analyze circuits is often associated with many years of learning, although this ability can also come from the use of many simple “tools” and short cuts. Fortunately, we can learn how to use these simple tools quite easily.

We can borrow a simple tool from the engineers and scientists which will simplify working with ac circuits. This simple tool is called a **VECTOR**. As we will use them, vectors are nothing more than lines which represent alternating voltages or currents. However, such simple lines allow us to add together voltages or currents that are “out of step.”

REPRESENTING VOLTAGES AND CURRENTS

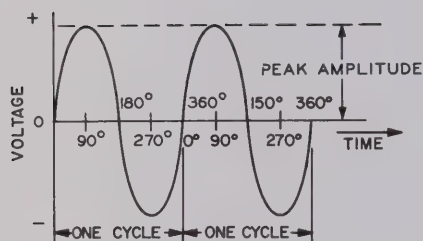


Figure
1

The curve of Figure 1 represents a voltage having a sinusoidal waveshape. This alternating voltage is constantly changing in amplitude and periodically reversing polarity. The drawing of the voltage in Figure 1 is called a “time presentation.” It shows how the voltage changes during a given period of time.

LENGTH
REPRESENTS
AMPLITUDE



Figure
2

In working with alternating voltages and currents, it is common practice to represent the voltage or current with a vector, which is a line drawn like an arrow. The length of the vector represents the peak amplitude of the voltage or current, as shown in Figure 2. To draw the vector, first let a given length represent so many volts. The length you choose is up to you. However, choose a length that is convenient. You don't want the vector larger than the paper you are drawing it on.

As an example, suppose you wish to represent a sinusoidal voltage with a peak amplitude of 200 volts. A convenient SCALE would be 100 volts equals 1 inch. The term “scale” is used to describe the length assigned to represent a given voltage or current. To represent the voltage in this example, you would draw the vector 2 inches long. Most rulers are divided into sixteenths between inch divisions. A convenient scale to use when drawing vectors is to let each small division, 1/16 inch, represent a given voltage or current.

In-Phase Voltages and Currents

When two voltages, two currents, or a voltage and a current wavelshape are in step (or phase), they can be shown as in Figure 3. Notice that waveform A goes higher and then lower than waveform B. Thus, waveform A would be represented by a longer vector than B. The two waveforms are in phase because they both cross the horizontal axis at the same point, they both reach their positive peaks at the same point (on the horizontal axis), and they both reach their negative peaks at the same horizontal point.

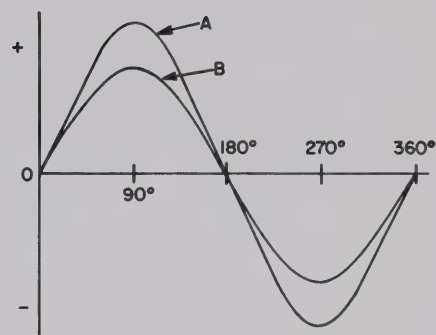


Figure
3

When drawing vectors for these two waveforms, we show them pointing in the same direction, as in Figure 4. The vector for voltage A is longer than the vector for B. Since the two vectors are pointing in the same direction, the phase angle between them is zero.

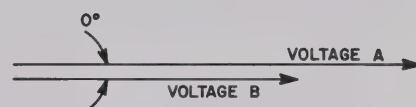


Figure
4

Out-of-Phase Voltages and Currents

In many ac circuits the voltages and currents are not in step or phase. The term **PHASE** is used to describe the angle of a voltage or current with respect to some reference. Vectors provide a convenient means of showing the phase relationship between out-of-phase voltages and currents. To show phase relations, the vector is drawn at an angle with respect to a reference line (usually horizontal), as shown in Figure 5. The angle between the vector and the reference line corresponds to the phase angle of the voltage or current. Figure 6A shows two sinusoidal waveforms. These could represent two voltages, two currents, or a voltage and a current. To illustrate the use of vectors, assume that both waveforms A and B are ac voltages. Notice that the two voltages are not in step or phase. At the 0-degree point of waveform A (0 voltage), waveform B is at the maximum voltage point. Waveform A will not reach the maximum voltage point until the 90-degree point. (The degree labels in the figure are for waveform A.)

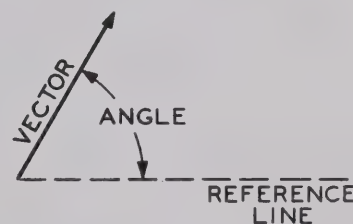
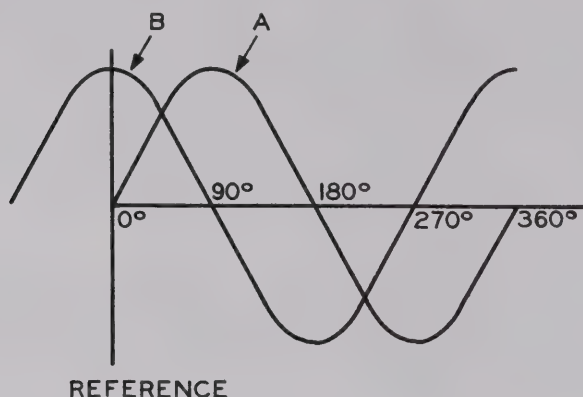


Figure
5

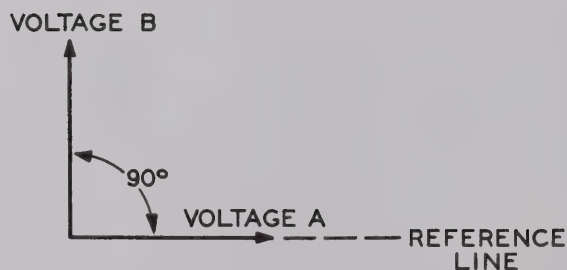
We can easily represent the conditions in Figure 6A with a vector diagram. Remember that a vector is a line drawn like an arrow. The length of the arrow represents the peak amplitude of the ac voltage or current. Since voltages A and B in Figure 6A have the same peak amplitude, the vectors representing them would have the same length.

To determine the phase relationship, and thus the angles at which to draw the vectors, one of the voltages must be used as a reference. Suppose that voltage A in Figure 6A is the reference. We can assign an angle or phase of 0 degrees to the vector of the reference voltage. Thus, its vector would

be drawn at 0 degrees (on top of) with respect to the reference line (or on top of the reference line, as shown in Figure 6B).



A

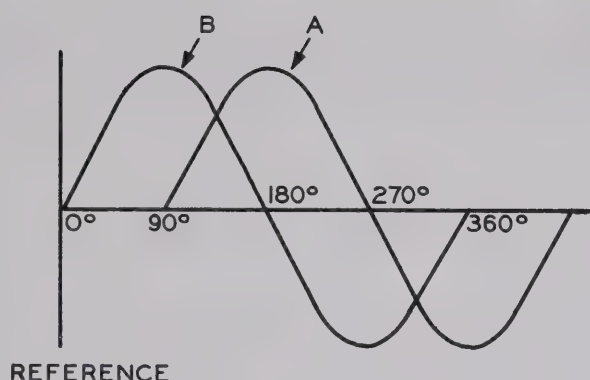


B

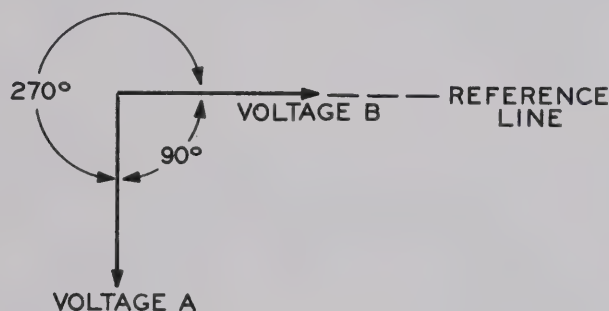
Figure 6

In Figure 6A, voltages A and B are shown 90 degrees apart, which means that they are 90 degrees out-of-phase. A vector representing voltage B would be drawn at an angle of 90 degrees with respect to the reference line, which is, in this example, the vector for voltage A. These vectors are shown in Figure 6B.

To show that one voltage is ahead or behind another, we assume that vectors move, or rotate, in a counterclockwise direction. Since voltage B starts out at its zero-degree point 90 degrees before voltage A, the vector for voltage B is drawn 90 degrees counterclockwise with respect to vector A. In this example, we would say that voltage B **LEADS** voltage A.



A



B

Figure 7

In Figures 6A and 6B, voltage B leads voltage A since voltage A is considered to be the reference. Changing the reference by 90 degrees reverses the situation. Figure 7A shows the voltages of Figure 6A with the reference changed by 90 degrees. The 0-degree point of voltage B is now the reference. Notice that voltage A passes through its zero-degree point 90 degrees after voltage B. Voltage A LAGS voltage B by 90 degrees. The leading vector was drawn in a counterclockwise direction in Figure 6B. In the vector diagram shown in Figure 7B, the vector for voltage A is drawn 90 degrees clockwise from the vector for voltage B. Voltage A is at an angle of 270 degrees from the reference line, since the angles are measured counterclockwise from the reference line.

One voltage or current can lead or lag the other, depending upon which is considered the reference. We normally use 180 degrees as the division between leading and lagging. A voltage or current starting anywhere between

0 and 180 degrees ahead of another is usually considered to be leading the other voltage or current. Beyond 180 degrees, a voltage or current is lagging another voltage or current by the number of degrees to the next cycle.

DRAWING VECTORS

For your convenience in drawing vectors, a combination scale-protractor is included with your materials. Figure 8 shows how to use the protractor to obtain a particular angle. First draw the horizontal reference line. If you draw the reference line in dashes, you will not mistake it for a vector. Then place the scale-protractor on the line. Line up the index mark with the end of the reference line as shown. Draw a mark at the desired angle. The angles we will use are printed on the inside edge of the protractor. In Figure 8 a mark is drawn at 50 degrees.

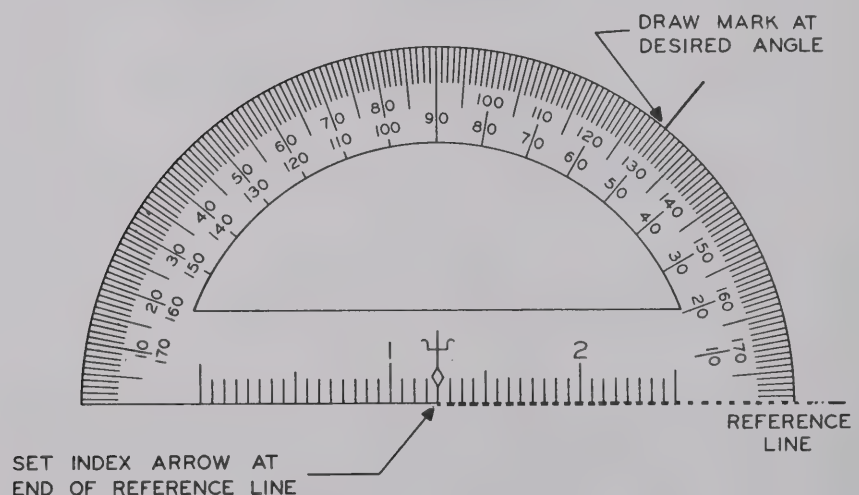


Figure 8

Let us draw a vector with an angle of 50 degrees and a length of $3 \frac{1}{2}$ inches, as shown in Figure 9. The $3 \frac{1}{2}$ inch division on the ruler is positioned at the end of the reference line while the straight edge of the ruler is positioned along the 50-degree mark that you have just made with the protractor. A line is then drawn along the straight edge from the upper end of the ruler to the end of the reference line. This is your vector. If each small scale division, $\frac{1}{16}$ inch, represents 5 volts, then the vector represents 280 volts. Now you may place an arrowhead at the upper end of the vector.

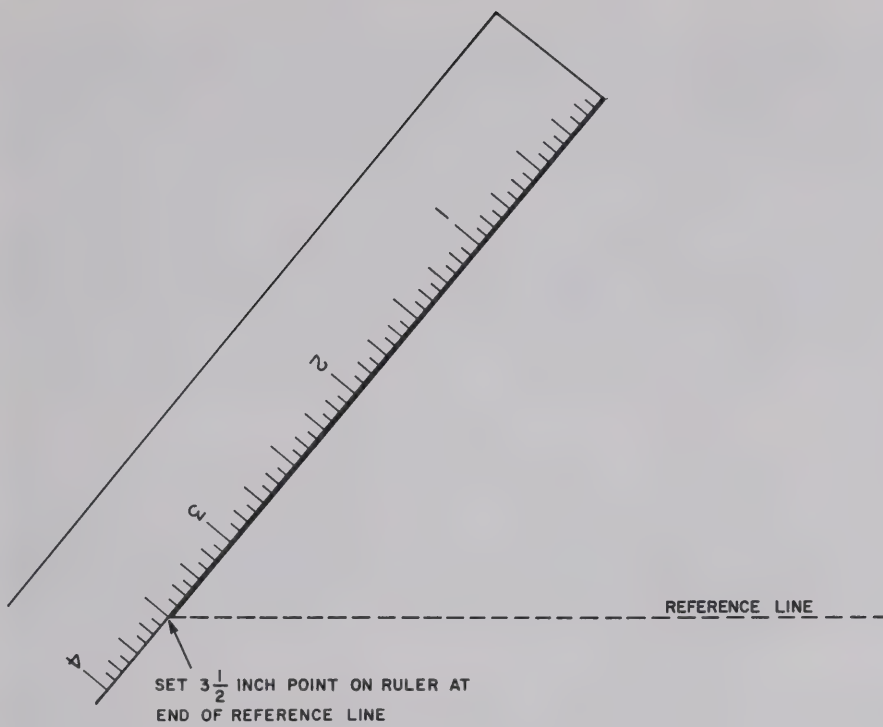


Figure 9

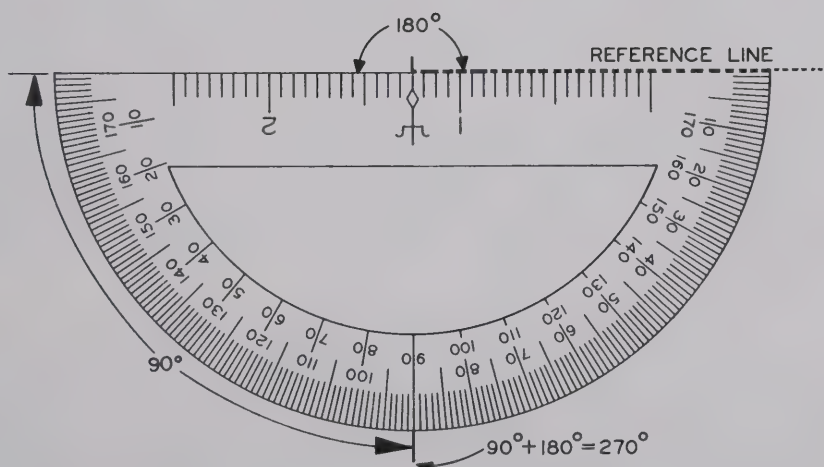


Figure 10

The protractor is not marked for angles greater than 180 degrees. However, it is simple to draw vectors at angles greater than 180 degrees. Position the protractor as shown in Figure 10. In this position, the protractor is moved 180 degrees (turned upside down) from the position shown in Figure 8. Therefore, you must add 180 degrees to the reading on the protractor scale to obtain the correct angle. To draw a vector at 270 degrees, draw a mark at the 90-degree point on the protractor as shown in Figure 10, since $180 \text{ degrees} + 90 \text{ degrees} = 270 \text{ degrees}$. If you want to draw a vector at 210 degrees, draw a mark at 30 degrees, since $180 \text{ degrees} + 30 \text{ degrees} = 210 \text{ degrees}$, and so on.

AC CIRCUITS

As mentioned earlier, the voltages and/or currents in an ac circuit are often out of step, or phase, with each other. This is because ac circuits usually contain inductance and capacitance in addition to resistance.

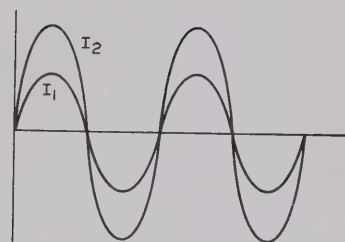


Figure 11

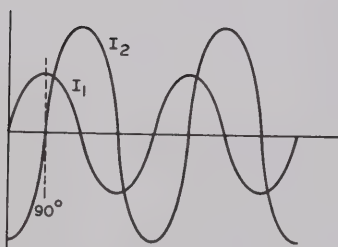


Figure 12

Figure 11 shows the conditions that would exist in a parallel ac circuit that contained only resistance. The two branch currents, I_1 and I_2 , are in phase, or in step, as were the vectors in Figure 3. Since the currents are in phase, we can add their values together to determine the total current. Conversely, Figure 12 shows the conditions that may occur in a practical parallel ac circuit. Notice that the two branch currents, I_1 and I_2 , are not in phase with each other. I_1 starts at 0-degrees, and I_2 is at its 270-degree point when it crosses the zero degrees vertical reference line.

The out-of-phase condition of Figure 12 is easier to picture if we use vectors to represent the currents. Since I_1 and I_2 are not in phase, we cannot add their values directly to determine the total circuit current. However, vectors provide a means of adding out-of-phase voltages or currents.

We will use vectors for the parallel ac circuit of Figure 13 where the currents in each branch are not in phase with each other. The current in Load 1 is at 20 degrees and the current in Load 2 is at 70 degrees. Rather than drawing actual current waveforms as in Figure 12, we can use vectors to show the relationship between I_1 and I_2 .

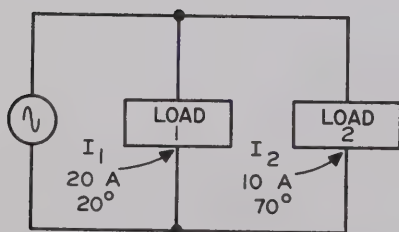


Figure 13

To represent I_1 with a vector, draw a vector whose length corresponds to the value of I_1 , 20 amperes. Suppose you let each small mark on the scale represent 1 ampere. You would draw the I_1 vector to a length of 20 small divisions, or 1 1/4 inches. Since I_1 has a phase angle of 20 degrees, you would draw the I_1 vector at an angle of 20 degrees from the horizontal reference line.

You must use the same scale, 1 ampere per small division, when you draw the vector for I_2 . Since I_2 has a value of 10 amperes, its length would be 10 small divisions, or 5/8 inch. The phase angle of I_2 is 70 degrees. Therefore, the I_2 vector is drawn at an angle of 70 degrees from the horizontal reference line.

Figure 14 shows the vector diagram for the circuit of Figure 13. Notice that the two vectors are drawn counterclockwise from the reference line. Since the I_2 vector has an angle greater than the I_1 vector, we can say that I_2 LEADS I_1 . The angle between I_1 and I_2 is 70 degrees — 20 degrees, or 50 degrees. Therefore, I_2 LEADS I_1 BY 50 DEGREES.

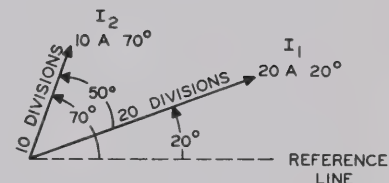


Figure 14

Figure 15 shows a series ac circuit in which the voltages are not in phase. To represent the voltages in the circuit with vectors, follow the same procedure as used for Figure 13. Draw a vector at the phase of E_1 with a length corresponding to the value of E_1 , 150V. Suppose you let each small scale division represent 10 volts. The E_1 vector would be 15 small divisions long at an angle of 0 degrees, or along the horizontal reference line.

Following the same procedure, draw the vector for E_2 . Since E_2 is 200V, the E_2 vector is 20 small divisions long. Since the E_2 phase angle is 270 degrees, the E_2 vector is drawn at 270 degrees. Figure 16 shows the vector diagram for this circuit.

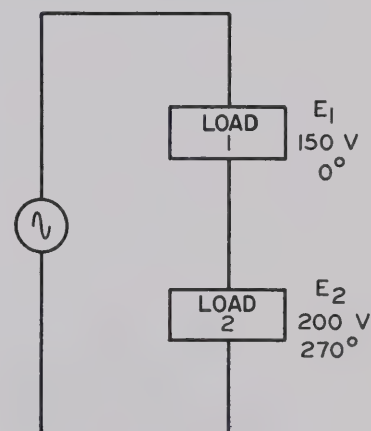


Figure 15

Remember that the angles are measured counterclockwise from the horizontal reference line.

Since the angle of the E_2 vector is larger than the angle of the E_1 vector, we can say that E_2 LEADS E_1 by 270 degrees. However, we usually use 180 degrees as a dividing point between leading and lagging. Therefore, it would be more convenient to say that E_2 LAGS E_1 . To determine the lag angle, determine the number of degrees in a counterclockwise direction from E_2 to E_1 . Since E_2 is at an angle of 270 degrees, it is 90 degrees away from the reference line and the E_1 vector. Therefore, E_2 LAGS E_1 BY 90 DEGREES. Note that we can also say that E_1 LEADS E_2 by 90 degrees.

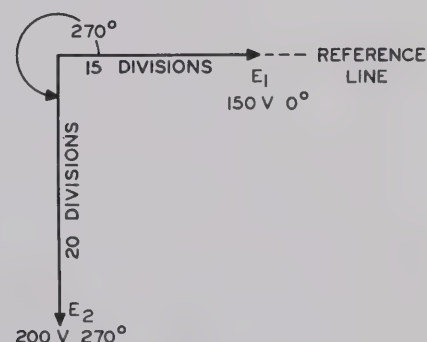


Figure 16

ADDING VOLTAGE VECTORS AND CURRENT VECTORS

Voltages or currents which are in phase or 180 degrees out-of-phase can be added or subtracted with ordinary arithmetic. However, voltages or currents which are out-of-phase cannot be added using conventional arithmetic.

Vectors are used to provide us with a simple means of adding out-of-phase voltages or currents.

In-Phase and 180-Degree Out-of-Phase Vectors

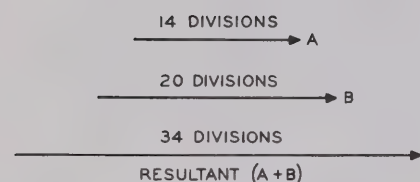


Figure 17

Sometimes you may find it necessary to add vectors that are in phase with each other. To add such vectors, merely add their values together. For example, Figure 17 shows two vectors, A and B. Both vectors have the same angle; therefore, they are in phase with each other. The length of the resultant vector is the sum of the lengths of the individual vectors. It does not make any difference what the angles are as long as the vectors have the SAME angle. For example, two vectors that lie in the 20-degree direction can be added directly; two vectors at 90 degrees can be added directly; etc. The resultant has the same angle as the two vectors that are added.

Another special case is where the vectors are 180 degrees apart. To determine the resultant vector, just subtract the smaller from the larger. The angle of the resultant is that of the larger vector.

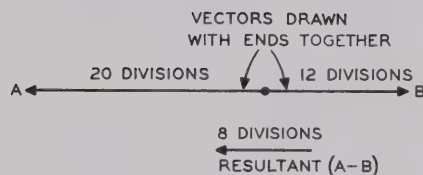


Figure 18

Figure 18 shows an example of vectors 180 degrees apart. Vector A is 20 small divisions long while vector B is 12 small divisions long. Note that the vectors are drawn end to end since they are 180 degrees out-of-phase. Subtracting vector B from vector A produces a resultant vector with a length of 8 small divisions. Since vector A is the longer of the two, the resultant vector has the same angle as vector A.

Vectors at Right Angles

When vectors are at right angles (90 degrees apart), the resultant vector (vector sum) can be found mathematically, as well as by the graphical method. The vector sum can be found by using the following expression:

$$\text{VECTOR SUM} = \sqrt{A^2 + B^2}$$

where: A and B are the vectors to be added.

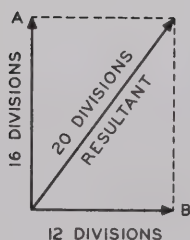


Figure 19

To illustrate the use of this formula, let's determine the length of the resultant vector in Figure 19. Vector A is 16 small divisions long and vector B is 12

The following Practice Exercise questions cover the subjects which you have just studied. They are:

REPRESENTING VOLTAGES AND CURRENTS

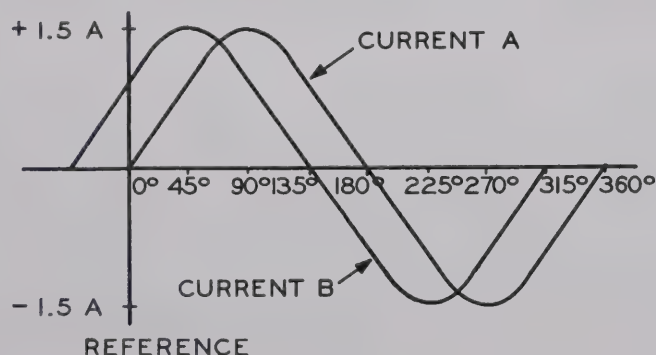
IN-PHASE VOLTAGES AND CURRENTS

OUT-OF-PHASE VOLTAGES AND CURRENTS

DRAWING VECTORS

AC CIRCUITS

1. What is a vector?
2. For a vector which represents a sinusoidal voltage or current, the vector's length corresponds to the (a) amplitude, (b) frequency.
3. Suppose that an ac current has a peak amplitude of 250 mA. How long would you draw a vector to represent this current if you let each small division on the ruler represent 10 mA?
4. Vectors are normally drawn in a _____ direction from the reference line.
5. In Figure 6A, voltage B leads voltage A. Is it also true that voltage A lags voltage B?
6. Draw the vector diagram to illustrate the phase relationship between the two currents shown. Use a scale of one inch equals one ampere. Current A is the reference.



7. A parallel ac circuit contains two branches. One branch contains pure resistance and has a current of 15 amperes at an angle of 0 degrees. The other branch contains a motor and has a current of 20 amperes at an angle of 75 degrees. Draw a separate vector diagram to represent each branch current. Let each small scale division on the scale-protractor represent 1 ampere.
8. When an ac induction motor is connected to an ac line, it presents a large inductance to the ac line. Under these conditions, would the motor voltage and current be in phase?
9. To determine the total peak current in Figure 12, you would just add together the peak values of I_1 and I_2 . True or False?
10. In Figure 14, I_2 (a) leads I_1 by 50 degrees, (b) lags I_1 by 50 degrees, (c) leads I_1 by 70 degrees.

small divisions long. The values are substituted into the expression as shown below:

$$\begin{aligned}
 \text{VECTOR SUM} &= \sqrt{A^2 + B^2} \\
 &= \sqrt{16^2 + 12^2} \\
 &= \sqrt{256 + 144} \\
 &= \sqrt{400} \\
 &= 20 \text{ small divisions.}
 \end{aligned}$$

The above answer agrees with the resultant value, which is determined as shown in Figure 19. You can use this simple expression whenever you want to determine the vector sum of two vectors at right angles. However, this formula applies **ONLY TO VECTORS AT RIGHT ANGLES**, or 90 degrees apart.

Figure 20 shows an alternate method of finding the resultant vector. Vector A is drawn first as it was in Figure 19. Then vector B is drawn from the head of vector A and parallel to the reference line (in the same direction as vector B in Figure 19). The resultant vector is drawn from the lower end of vector A to the head of vector B. The resultant vectors of the two figures are the same.

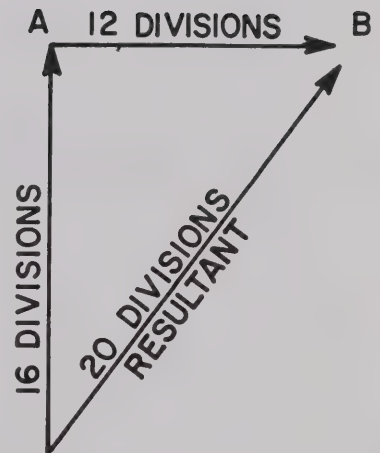


Figure 20

Out-of-Phase Vectors

The vectors for the circuit of Figure 13 are redrawn in Figure 21. Since the currents are out-of-phase with each other (they do not have the same phase angle), the total current cannot be found by adding them directly. Direct addition can only be used for in-phase currents.

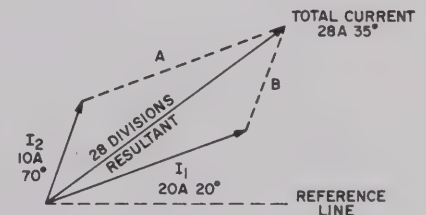


Figure 21

To determine the total current, draw a line parallel to the I_1 vector, beginning at the I_2 arrowhead. This is the dashed line labeled A in Figure 21. Next, draw a line parallel to the I_2 vector, beginning at the I_1 arrowhead. This is the dashed line labeled B in Figure 21. To determine the total current, draw a vector from the intersection of the two vectors I_1 and I_2 to the intersection of the two lines A and B. This vector is called the **RESULTANT** and it represents the total circuit current.

To find the value of the total current, measure the length of the resultant vector. That's all there is to it! The resultant vector in Figure 21 is about 28 small divisions long. Since each small division represents 1 ampere, the total current is about $28 \text{ divisions} \times 1 \text{ ampere} = 28 \text{ amperes}$.

To determine the phase of the total current, just measure the angle of the total current: its about 35 degrees in Figure 21.

The graphical method shown in Figure 21 is called **VECTOR ADDITION** because the method yields the "sum" of the two vectors. DO NOT confuse this type of addition with the conventional way of adding.

In working with ac circuits, you will find that a 90-degree phase shift is common. Finding the resultant under these conditions is much simpler than when the phase shift is greater or less than 90 degrees.

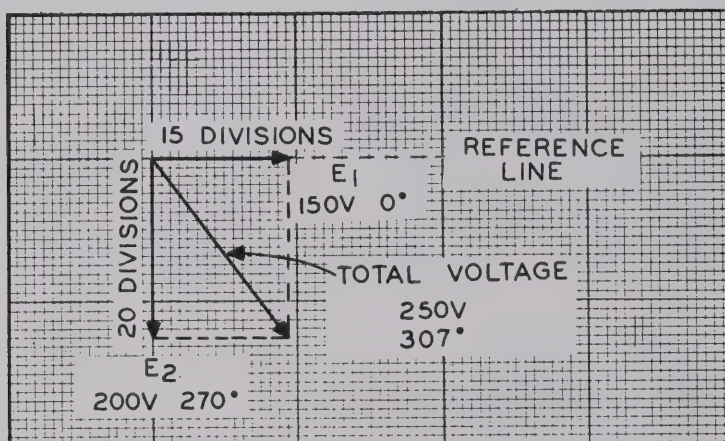


Figure 22

The vector diagram for the circuit of Figure 15 is redrawn in Figure 22. To find the resultant, two dashed lines are again drawn, one parallel to the E_1 vector and the other parallel to the E_2 vector. To determine the total voltage, the resultant vector is drawn from the intersection of the E_1 and E_2 vectors to the intersection of the dashed lines. Measure the length of the resultant vector to determine the total voltage. By drawing the vector diagram on graph paper as shown, it is a simple matter to draw the additional parallel lines to determine the resultant vector. Remember, this is a graphical procedure and your answers are only as accurate as your drawing.

In Figure 22, the resultant vector is approximately 25 small divisions in length. Since each small division represents 10 volts, the value of the resultant vector is $25 \text{ divisions} \times 10 \text{ volts} = 250 \text{ volts}$. To determine the phase angle of the total voltage, measure the angle of the resultant vector. The measured phase angle in Figure 22 is about 307 degrees counterclockwise from the horizontal reference line. For convenience, we would probably say that the resultant vector lags the horizontal reference (and E_1 which lies on the horizontal reference line) by $360 \text{ degrees} - 307 \text{ degrees}$, or 53 degrees. Also, the resultant leads the E_2 vector by $307 \text{ degrees} - 270 \text{ degrees}$, or 37 degrees.

You can use vectors to determine the resultant of more than two out-of-step voltages or currents. To illustrate the method used, let's determine the total current in the circuit of Figure 23. First, find the vector sum or resultant of any two of the currents. Then, use this resultant and the third current to find their resultant, which is the total circuit current.

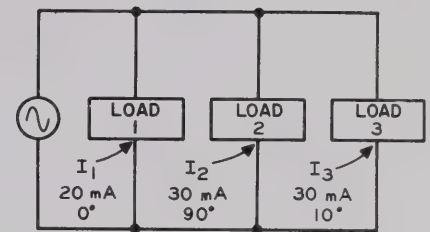


Figure 23

Let's first find the vector sum of I_1 and I_2 in Figure 23. To set up a convenient scale let each small division represent 1 mA. The I_1 vector will be 20 small scale divisions in length and the I_2 vector will be 30 small scale divisions in length. Draw the I_1 vector at 0 degrees along the horizontal reference and draw the I_2 vector at 90 degrees, as shown in Figure 24. To obtain the resultant vector (vector sum of I_1 and I_2), draw dashed lines parallel to I_1 and I_2 , and draw the resultant vector to the intersection of the dashed lines, as shown in the figure. The length of the resultant vector is approximately 36 small scale divisions and its angle is about 56 degrees. Therefore, the vector sum of I_1 and I_2 is $36 \text{ divisions} \times 1 \text{ mA} = 36 \text{ mA}$, at 56 degrees.

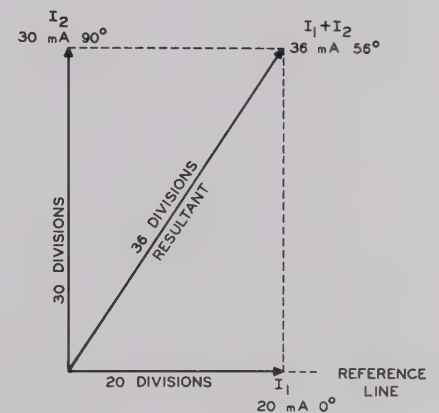


Figure 24

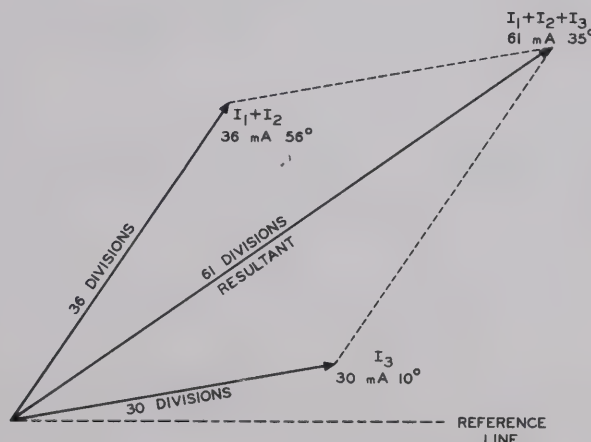


Figure 25

Now, combine the resultant vector of I_1 and I_2 shown in Figure 24 with the I_3 vector, as shown in Figure 25. Use the regular procedure to find the resultant (vector sum). The resultant vector in Figure 25 is approximately 61 small divisions in length and it is at an angle of about 35 degrees. Since each small division represents 1 mA, the total circuit current is 61 divisions $\times$ 1 mA = 61 mA, at an angle of 35 degrees. You will have to use the ruler as shown in Figure 9 to measure the resultant vector. If the circuit contained another branch, you would then combine its vector with the resultant vector of Figure 25. In this example, we have considered the current vectors in a parallel circuit. The same method can be used to combine out-of-phase voltages in a series circuit.

COMPARING VOLTAGES AND CURRENTS

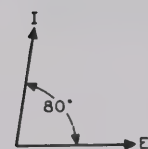


Figure
26

Vectors can be used to compare voltages and currents in a circuit. In this application, the vectors are not added or subtracted; they just provide us with a simple means of representing the conditions in an ac circuit. Figure 26 shows such a vector diagram. This diagram shows us that there is an 80-degree phase difference between voltage and current. This could be represented by drawing the sinewaves for the voltage and current. However, this type of diagram would be more difficult to interpret. The vector diagram is easy to understand.

Because vector angles are measured COUNTERCLOCKWISE from the reference, the I vector of Figure 26 LEADS the E vector. That is, THE CURRENT LEADS THE VOLTAGE by 80 degrees.

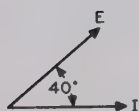


Figure
27

Figure 27 shows another vector diagram. This diagram shows the E vector 40 degrees counterclockwise, or ahead of the I vector. It shows that THE VOLTAGE LEADS THE CURRENT by 40 degrees.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

ADDING VOLTAGE VECTORS AND CURRENT VECTORS

IN-PHASE AND 180-DEGREE OUT-OF-PHASE VECTORS

VECTORS AT RIGHT ANGLES

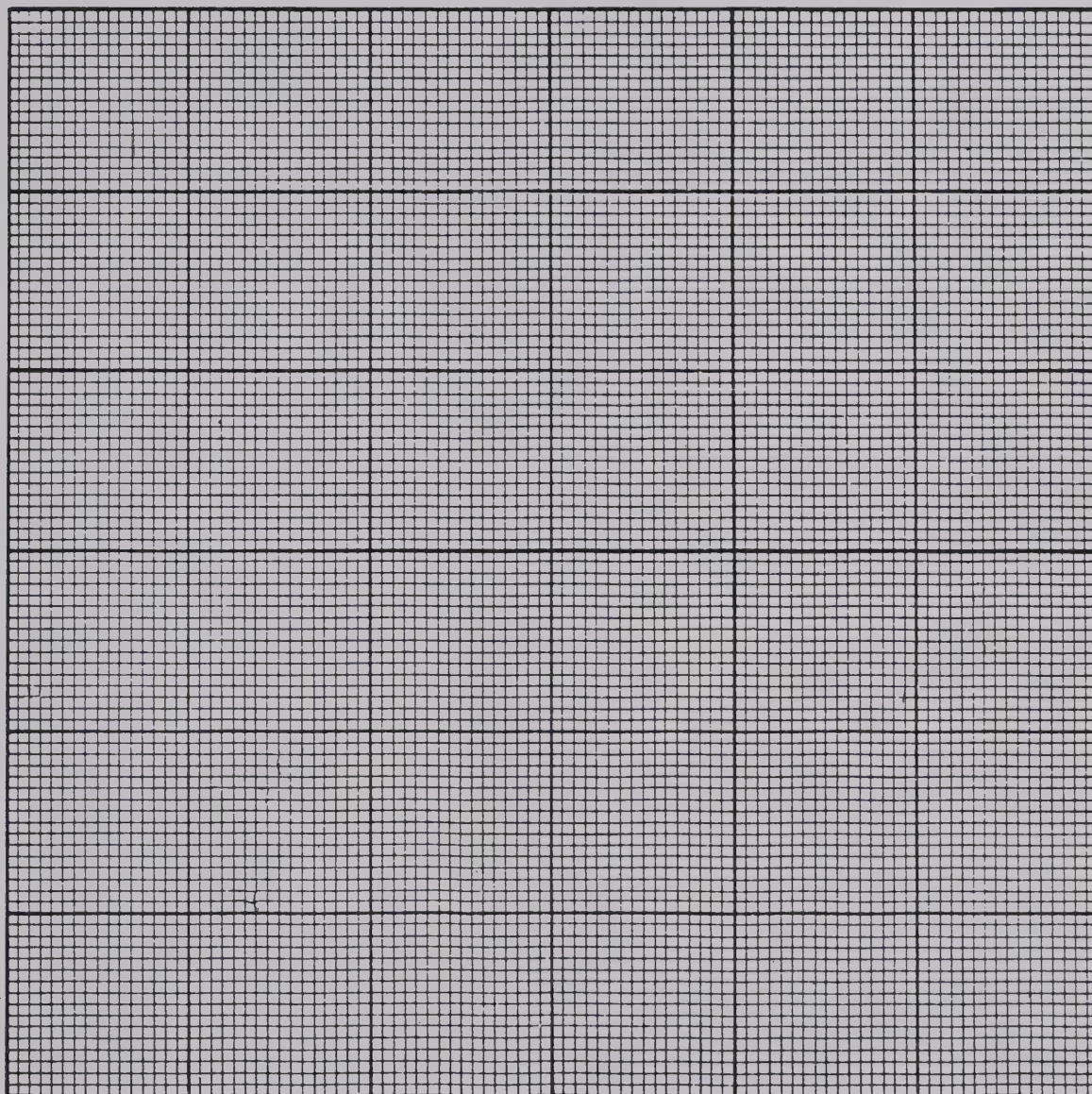
OUT-OF-PHASE VECTORS

COMPARING VOLTAGES AND CURRENTS

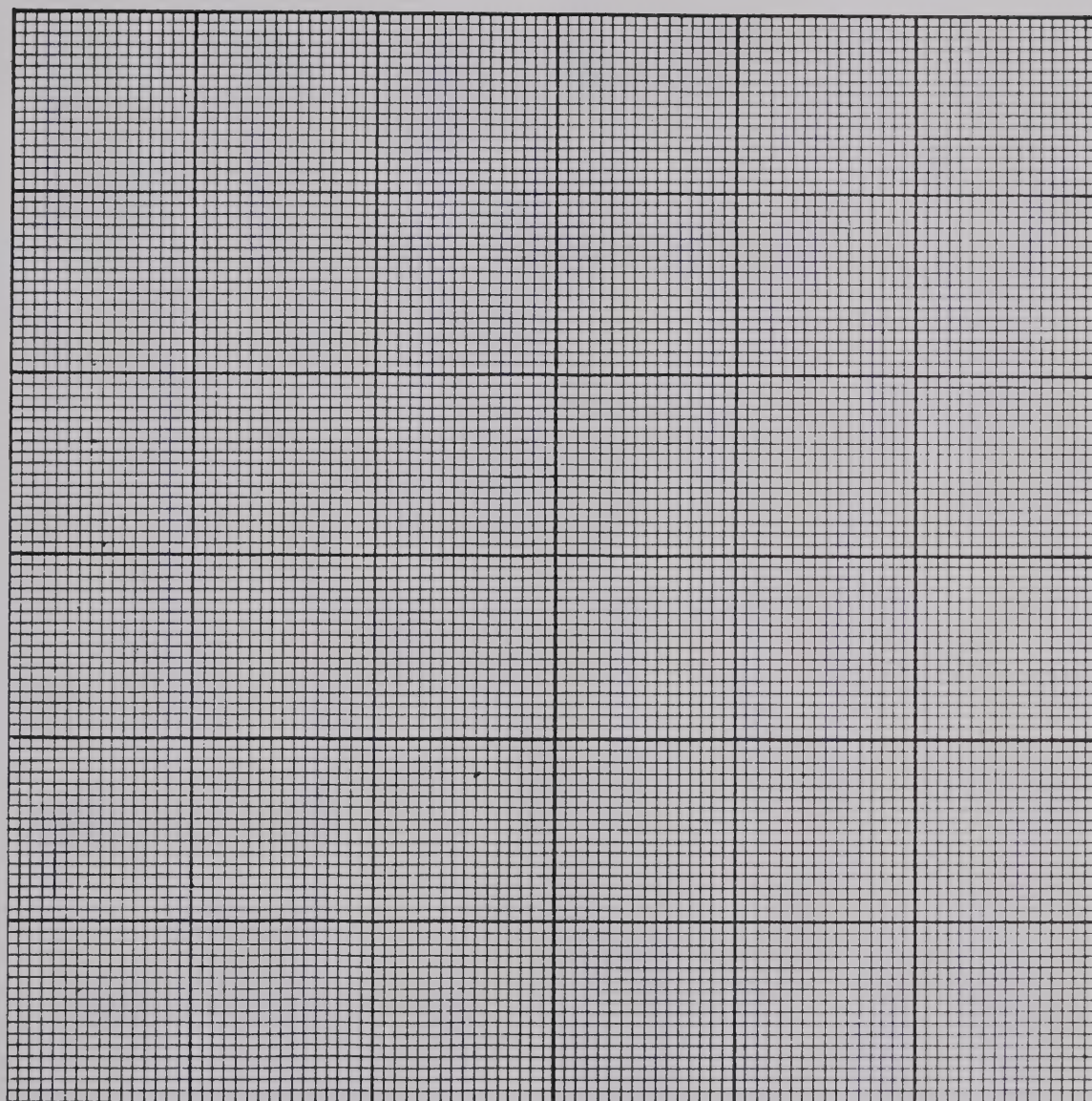
11. What is a resultant vector?
12. How do you determine the value of a resultant vector?
13. What name is given to the process of determining the resultant vector?
14. Suppose that a series circuit contains two components. The voltage across one component, E_1 , is 150 volts at a phase angle of 0 degrees. The voltage across the other component, E_2 , is 150 volts at a phase angle of 90 degrees. Using a scale of 5 volts per small scale division, draw a vector diagram to determine the total circuit voltage. Graph paper is included at the end of this set of questions for the vector diagram. The graph paper is divided into sixteenths of an inch to match the scale on your scale-protractor.
15. Besides the regular graphical method, how can you determine the vector sum of two vectors, A and B, at right angles to each other?
16. A parallel circuit contains two branches. The current in one branch is 6 amperes at 0 degrees and the current in the other branch is 8 amperes at 90 degrees. Using the formula, determine the vector sum.

17. How do you determine the resultant of two vectors that are 180 degrees apart?
18. A series circuit contains three components. The voltage across one component, E_1 , is 150 volts at an angle of 0 degrees, the voltage across the second component, E_2 , is 150 volts at an angle of 90 degrees and the voltage across the third component, E_3 , is 250 volts at an angle of 270 degrees. What is the total circuit voltage? Use the graph provided at the end of this set of questions for your solution. Use a scale of one small division (1/16 inch) equals 10 volts.

USE THIS GRAPH FOR THE SOLUTION TO
PRACTICE EXERCISE 14



USE THIS GRAPH FOR THE SOLUTION TO
PRACTICE EXERCISE 18



SUMMARY

Conventional addition cannot be used to combine voltages or currents that are not in step or in phase. Vectors provide a simple means of adding out-of-phase voltages or currents. They also provide a simple means of representing ac voltages.

A vector is drawn like an arrow. Its length represents the amplitude of the current or voltage being represented. The angle of the vector from the reference line corresponds to the angle or phase of the voltage or current being represented.

To determine the sum of two out-of-phase voltages or currents, you draw vectors to represent the voltages or currents. By drawing a resultant vector, you can determine the total voltage or current. This total voltage or current is called the vector sum. However, a voltage vector and a current vector cannot be added.

When vectors are 90 degrees out-of-phase, their vector sum can be found mathematically, as well as by the use of vectors.

The following formula is used for finding the sum of two vectors that are 90 degrees out-of-phase:

$$\text{VECTOR SUM} = \sqrt{A^2 + B^2}$$

when A and B represent the lengths of the vectors to be added.

If vectors are in phase (they have the same angle), you can find their sum by simply adding their values together. If vectors are 180 degrees out-of-phase, you find their resultant value by subtracting the smaller from the larger. The angle of the resultant is the angle of the larger vector.

IMPORTANT DEFINITIONS

PHASE — The position or angle of a sinusoidal voltage or current with respect to a reference.

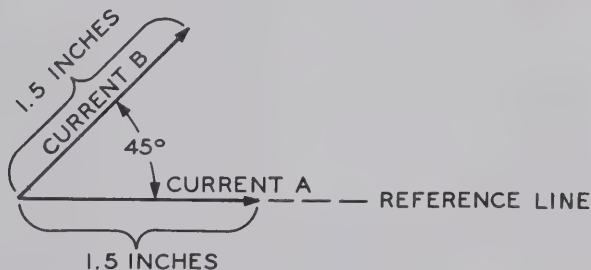
RESULTANT — A vector which is the sum of two or more vectors.

VECTOR — A line drawn like an arrow, that is used to represent a quantity.
The length of the vector corresponds to the magnitude of the quantity.
The angle of the vector corresponds to the direction or angle of the quantity with respect to a reference.

VECTOR ADDITION — A graphical procedure for determining the sum of two or more vectors.

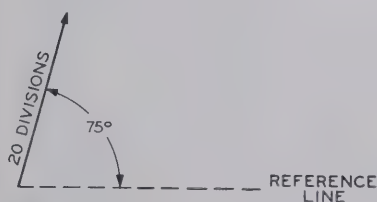
PRACTICE EXERCISE SOLUTIONS

1. A vector is a line drawn like an arrow, which represents the peak amplitude of a voltage or a current.
2. (a) amplitude.
3. 25 small divisions ($25 \times 1/16 \text{ inch} = 1-9/16 \text{ inches}$).
4. counterclockwise — It is common practice to draw vectors in a counterclockwise direction.
5. Yes — If voltage B leads voltage A, we can also say that voltage A lags voltage B.
6. Since the peak amplitude of each current is 1.5 amperes and the scale chosen is 1 ampere = 1 inch, the vectors for currents A and B would be 1.5 inches long. The vector for current B would be drawn 45 degrees counterclockwise from vector A, as shown in the drawing below.



7.

MOTOR CURRENT
20 A 75°

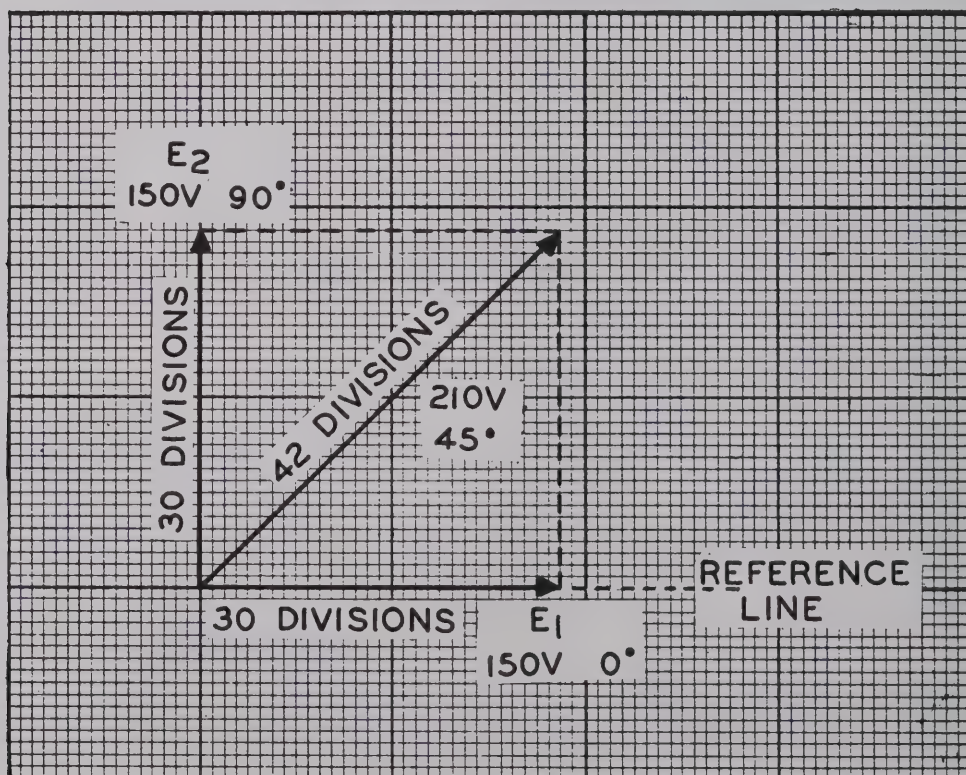


CURRENT THROUGH
PURE RESISTANCE
15 A 0°



PRACTICE EXERCISE SOLUTIONS (Continued)

8. No — The motor's inductance would cause the voltage and the current to be out of phase.
9. False — Since the currents are out of phase, they cannot be added together directly to determine the total peak current.
10. (a) leads I_1 by 50 degrees.
11. A resultant vector is a vector that represents the sum of two vectors.
12. First you measure the length of the resultant vector. Then multiply its length by the scale used. For example, if the vector is 25 small scale divisions in length and the scale is 1 mA per small division, the resultant vector has a value of $25 \times 1 \text{ mA} = 25 \text{ mA}$.
13. Vector addition.
- 14.



PRACTICE EXERCISE SOLUTIONS (Continued)

15. The vector sum formula can be used:

$$\text{VECTOR SUM} = \sqrt{A^2 + B^2}$$

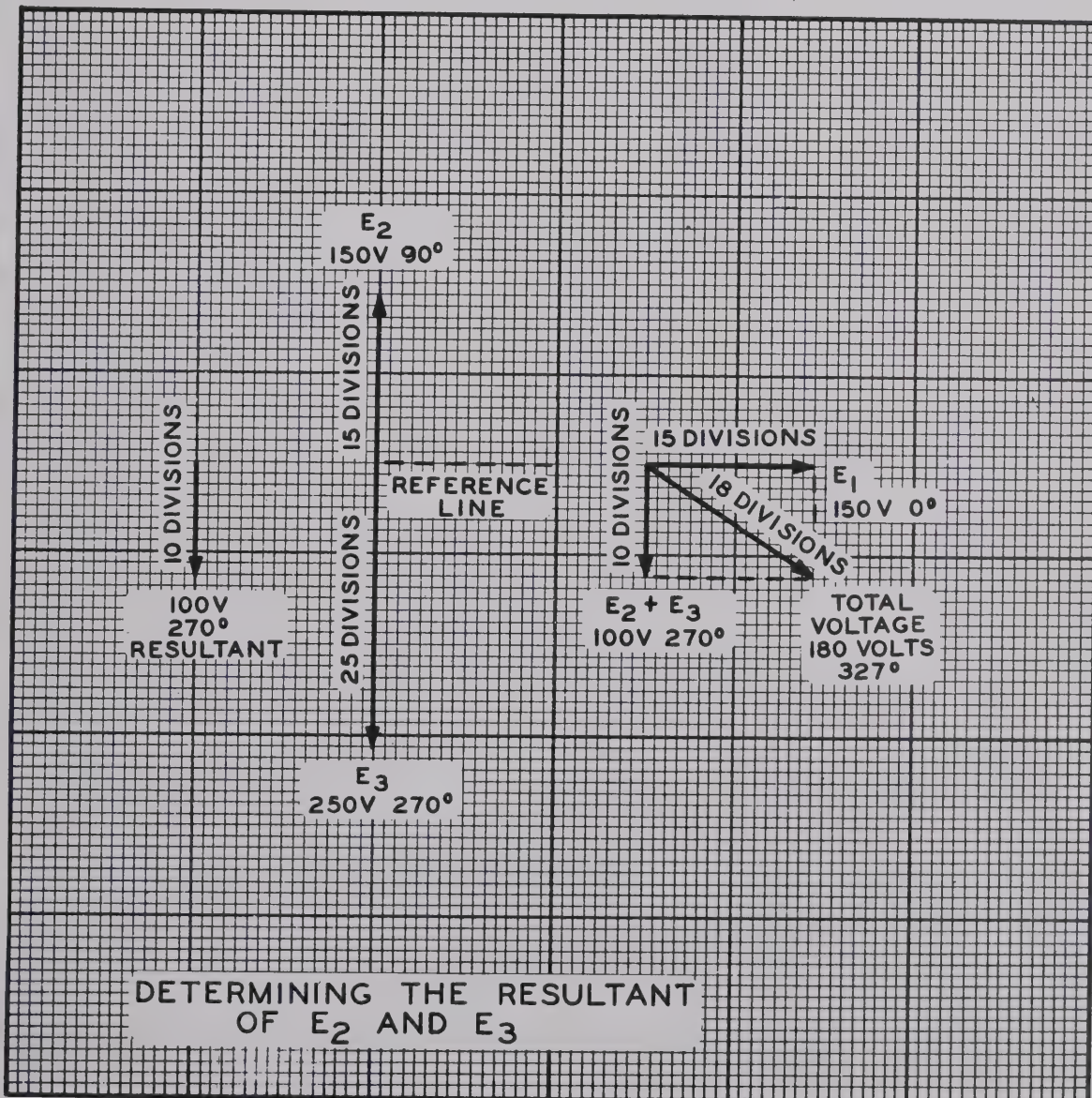
where: A and B are the vectors.

16. 10 amperes — The vector sum is found using the formula as follows:

$$\text{VECTOR SUM} = \sqrt{A^2 + B^2} = \sqrt{6^2 + 8^2} = \sqrt{36 + 64} = \sqrt{100} \\ = 10 \text{ amperes.}$$

17. You subtract the smaller from the larger. The angle of the resultant is the same as the angle of the larger vector.

18.



NOTICE: To keep our lessons up-to-date, we add material to the texts from time to time, and make occasional changes in the examination questions. Therefore, when checking your answers with this check sheet, look at the code LETTER (A, B, C, etc.) on your examination sheet to determine which of the following groups of answers apply to the lesson which you have.

1058B

1. C - THE LENGTH OF A VECTOR REPRESENTS -- AMPLITUDE.

The length of a vector generally represents the peak amplitude of the voltage or current represented.

2. B - THE ANGLE OF A VECTOR WITH RESPECT TO THE REFERENCE LINE REPRESENTS -- PHASE.

The angle of the vector represents the phase of the voltage or current being measured.

3. C - USING A SCALE OF 10 VOLTS PER SMALL SCALE DIVISION, THE LENGTH OF A VECTOR WHICH REPRESENTS A SINUSOIDAL VOLTAGE WITH AN RMS AMPLITUDE OF 100 VOLTS IS APPROXIMATELY -- 14 SMALL DIVISIONS.

The length of a vector represents the peak amplitude of a voltage. Thus, the vector must represent an amplitude of 100 volts $\times$ 1.414 or 141.4 volts. Since each small division represents 10 volts, the vector length is 141.4/10 or approximately 14 small divisions.

4. C - IF A SINUSOIDAL CURRENT HAS A PHASE ANGLE OF 30°, ITS VECTOR SHOULD BE DRAWN AT -- 30°.

The angle of the vector with respect to the reference is the same as the angle of the current.

5. A - IN THE DIAGRAM OF FIGURE 12 -- I₂ LAGS I₁.

Since the zero crossing point of I₂ is 90 degrees behind I₁, I₂ lags I₁.

6. A - WHAT IS THE TOTAL VOLTAGE IN A SERIES CIRCUIT IF THE VOLTAGES ACROSS THE TWO COMPONENTS ARE 3 VOLTS AT AN ANGLE OF 0 DEGREES AND 4 VOLTS AT AN ANGLE OF 90 DEGREES? -- 5 VOLTS.

Since the angle between the two voltages is 90 degrees, the vector sum formula can be employed. The problem can also be solved graphically.

$$E_S = \sqrt{E_1^2 + E_2^2} = \sqrt{3^2 + 4^2} = \sqrt{9 + 16} = \sqrt{25} = 5 \text{ volts.}$$

7. A - THE RESULTANT VECTOR IN THE VECTOR DIAGRAM OF FIGURE 24 -- REPRESENTS THE VECTOR SUM OF I₁ AND I₂.

The vector sum of two vectors is obtained graphically by drawing the resultant vector.

8. A - THE RESULTANT VECTOR IN A CERTAIN VECTOR DIAGRAM HAS A LENGTH OF 26 SMALL SCALE DIVISIONS. WHAT IS ITS VALUE IF EACH SMALL DIVISION REPRESENTS 10 mA? -- 260 mA.

Since each small scale division has a value of 10 mA, the resultant vector has a value of 10 $\times$ 26 or 260 mA.

9. B - WHEN VECTORS ARE 180 DEGREES OUT-OF-PHASE, THE RESULTANT IS FOUND BY -- SUBTRACTING THE SMALLER FROM THE LARGER.

When vectors are 180 degrees out-of-phase, they are subtracted to find the resultant and when they are in phase, they are added to find the resultant.

10. C - IN FIGURE 27 -- E LEADS I.

Since the angle of E is greater than that of I, E leads I. We can also say that I lags E.

1058A

All explanations are the same as for 1058B except for those given below.

5. A - IN THE DIAGRAM OF FIGURE 10 -- I₂ LAGS I₁.

Since the zero crossing point of I₂ is 90 degrees behind I₁, I₂ lags I₁.

6. A - WHAT IS THE TOTAL VOLTAGE IN A SERIES CIRCUIT IF THE VOLTAGES ACROSS THE TWO COMPONENTS ARE 3 VOLTS AT AN ANGLE OF 0°, AND 4 VOLTS AT AN ANGLE OF 90°? -- 5 VOLTS.

Since the angle between the two voltages is 90°, the vector sum formula can be employed. The problem can also be solved graphically.

$$E_S = \sqrt{E_1^2 + E_2^2} = \sqrt{3^2 + 4^2} = \sqrt{9 + 16} = \sqrt{25} = 5 \text{ volts.}$$

QUESTIONS

IMPORTANT — These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
1058B

Example: A ruler is used to

A	☐
B	☒
C	☐
D	☐

A. drill holes. B. measure distance. C. open cans.
D. apply paint.

1. A ☐ The **LENGTH** of a vector represents
 B ☐ (A) frequency. (B) phase angle. (C) amplitude. (D) time.
 C ☒
 D ☐

2. A ☐ The **angle of a vector with respect to the reference line** represents
 B ☒ (A) magnitude. (B) phase. (C) amplitude. (D) velocity.
 C ☐
 D ☐

3. A ☐ Using a scale of 10 volts per small scale division, the length of a vector which
 B ☐ represents a sinusoidal voltage with an rms amplitude of 100 volts is approximately
 C ☒ (A) 10 small divisions. (B) 7 small divisions. (C) 14 small divisions. (D) 16 small
 D ☐ divisions.

4. A ☐ If a sinusoidal current has a phase angle of 30 degrees, its vector should be
 B ☐ drawn at
 C ☒ (A) 45 degrees. (B) 60 degrees. (C) 30 degrees. (D) 90 degrees.
 D ☐

5. A ☒ In the diagram of Figure 12,
 B ☐ (A) I_2 lags I_1 . (B) I_1 lags I_2 . (C) I_2 leads I_1 . (D) I_1 and I_2 are the same.
 C ☐
 D ☐

6. A ☒ What is the total voltage in a series circuit if the voltages across the two components
 B ☐ are 3 volts at an angle of 0 degrees and 4 volts at an angle of 90 degrees?
 C ☐ (A) 5 volts. (B) 15 volts. (C) 8 volts. (D) 2 volts.
 D ☐

7. A ☒ The resultant vector in the vector diagram of Figure 24
 B ☐ (A) represents the vector sum of I_1 and I_2 . (B) represents the difference between I_1
 C ☐ and I_2 . (C) is in phase with I_1 . (D) is in phase with I_2 .
 D ☐

8. A ☒ The resultant vector in a certain vector diagram has a length of 26 small scale
 B ☐ divisions. What is its value if each small division represents 10 mA?
 C ☐ (A) 260 mA. (B) 2600 mA. (C) 200 mA. (D) 26 mA.
 D ☐

9. A ☐ When vectors are 180 degrees out-of-phase, the resultant is found by
 B ☒ (A) adding the smaller to the larger. (B) subtracting the smaller from the larger.
 C ☐ (C) subtracting the larger from the smaller. (D) dividing the larger by the smaller.
 D ☐

10. A ☐ In Figure 27
 B ☐ (A) I and E are 90 degrees out-of-phase. (B) I leads E. (C) E leads I. (D) E and
 C ☒ I are in phase.
 D ☐

(

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((q

EXPERIMENT 6

VACUUM TUBE CIRCUITS— CATHODE FOLLOWER AMPLIFIERS

PARTS NEEDED

- | | |
|--|--------------------------------------|
| 1 - Multimeter with Test Leads and Spring Adapters | 1 - 4.7 k Ω , 1/2 W, Resistor |
| 1 - Partially Completed Design Console | 1 - 470 k Ω , 1/2 W, Resistor |
| - Modular Connectors | 1 - 12AU7 Vacuum Tube |
| 1 - 1 k Ω , 1/2 W, Resistor | 1 - 9-Pin Tube Socket with Leads |
| | - No. 22 Solid Hookup Wire |

OBJECTIVE

Cathode follower amplifier (also known as common or grounded-plate amplifier) circuits will be analyzed in this experiment. While the conventional common-cathode (or grounded-cathode) amplifier has a high voltage gain, the cathode follower has a voltage gain just under 1. In addition, the common-plate stage has a higher input impedance and a lower output impedance than the common-cathode stage. The grounded-plate amplifier is often employed for impedance matching or isolation (where changes in the conditions of the stage following a cathode follower are not allowed to affect the stage preceding the cathode follower). Note that what is meant by "grounded" as in the "grounded plate" circuit is that the plate is connected to ground as far as the signal is concerned (usually through sufficiently large de-coupling capacitors). Common-cathode circuits may have the cathodes connected to a dc ground as well as to an ac ground. Note also that "common" and "grounded" have the same meaning; "common-plate" is the same as "grounded-plate."

PROCEDURE

CATHODE FOLLOWER AMPLIFIER

1. Construct the cathode follower circuit of Figure 6-1, following the layout of Figure 6-2. Make sure that the design console is turned off while constructing the circuit. Do not connect the jumper wire (at the grid) into the circuit at this time. Note that there is only an ac ground in this particular plate circuit. The capacitor providing this ac ground is the filter capacitor in the high voltage power supply.

The tapped cathode bias resistor arrangement is used to provide the correct grid bias. Remember, in this circuit, the cathode is at a higher dc voltage than in a normal grounded-cathode amplifier and the high voltage requires extra care. If the grid resistor R_3 were returned directly to ground, a higher bias would be provided, thus increasing the grid signal drive requirements

Vacuum Tube Circuits - Cathode Follower Amplifiers

(the amplifier would then have a lower gain).

2. Turn on the design console. The regulated voltage selector switch can be left at either the 6 or 30 volt position, since the low voltage supply is not used. Set the Adjust Voltage control fully counterclockwise.

3. Measure the voltages at the V_1 plate and cathode, as well as the voltage at the junction of R_1 and R_2 , point Y. Remember, unless otherwise noted, all voltages are measured with respect to GND.

V_1 Plate Voltage 195 volts dc

V_1 Cathode Voltage 32 volts dc

Point Y Voltage 26 volts dc

Note that the V_1 plate voltage is equal to the supply voltage.

4. The actual V_1 grid bias voltage is the voltage drop across R_1 . To find this voltage, subtract the Point Y voltage from the V_1 cathode voltage.

V_1 Grid Bias 6 volts dc

5. Turn off the design console while making the following connection. To apply a test signal to the circuit, connect the jumper wire into the circuit. This applies a 6.3 volt ac signal to the grid circuit.

6. Turn on the design console. Using the output function of your multimeter, measure the ac signal input voltage at the grid and the ac output voltage at the cathode. Record the values below. Turn off the design console.

AC Input Voltage 7.3 volts ac

AC Output Voltage 5.4 volts ac

7. The voltage gain of an amplifier is equal to the output voltage divided by the input voltage. Calculate the voltage gain and record below.

$$\text{Voltage Gain } (A_V) = \frac{\text{AC Output Voltage}}{\text{AC Input Voltage}} = \frac{5.4}{7.3} = .72$$

Your calculated voltage gain should be less than 1. The output signal of a cathode follower circuit is always less than the input (but usually only slightly less).

Vacuum Tube Circuits - Cathode Follower Amplifiers

CONCLUSION

With the cathode-follower (grounded-plate) circuit, the voltage gain is always less than one; on the other hand, the grounded-cathode amplifier provides a voltage gain much greater than one. The grounded-plate amplifier is often used as an impedance matching circuit. The cathode follower has a high input impedance and a low output impedance.

$$\begin{array}{r} 72 \\ 73 \overline{) 5400} \\ \underline{521} \\ 190 \end{array}$$

NOTES

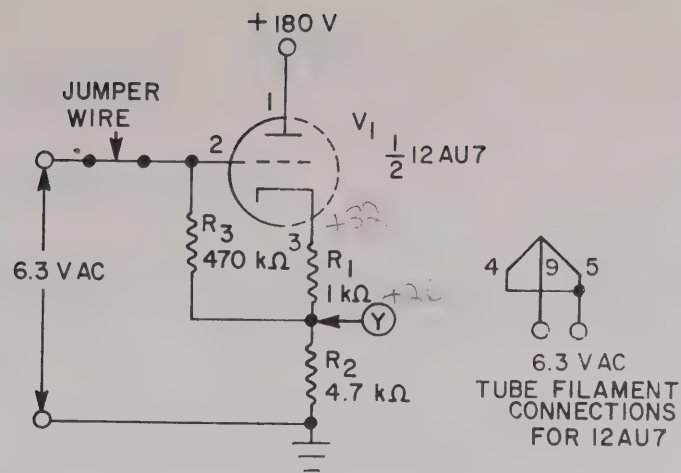


FIGURE 6-1

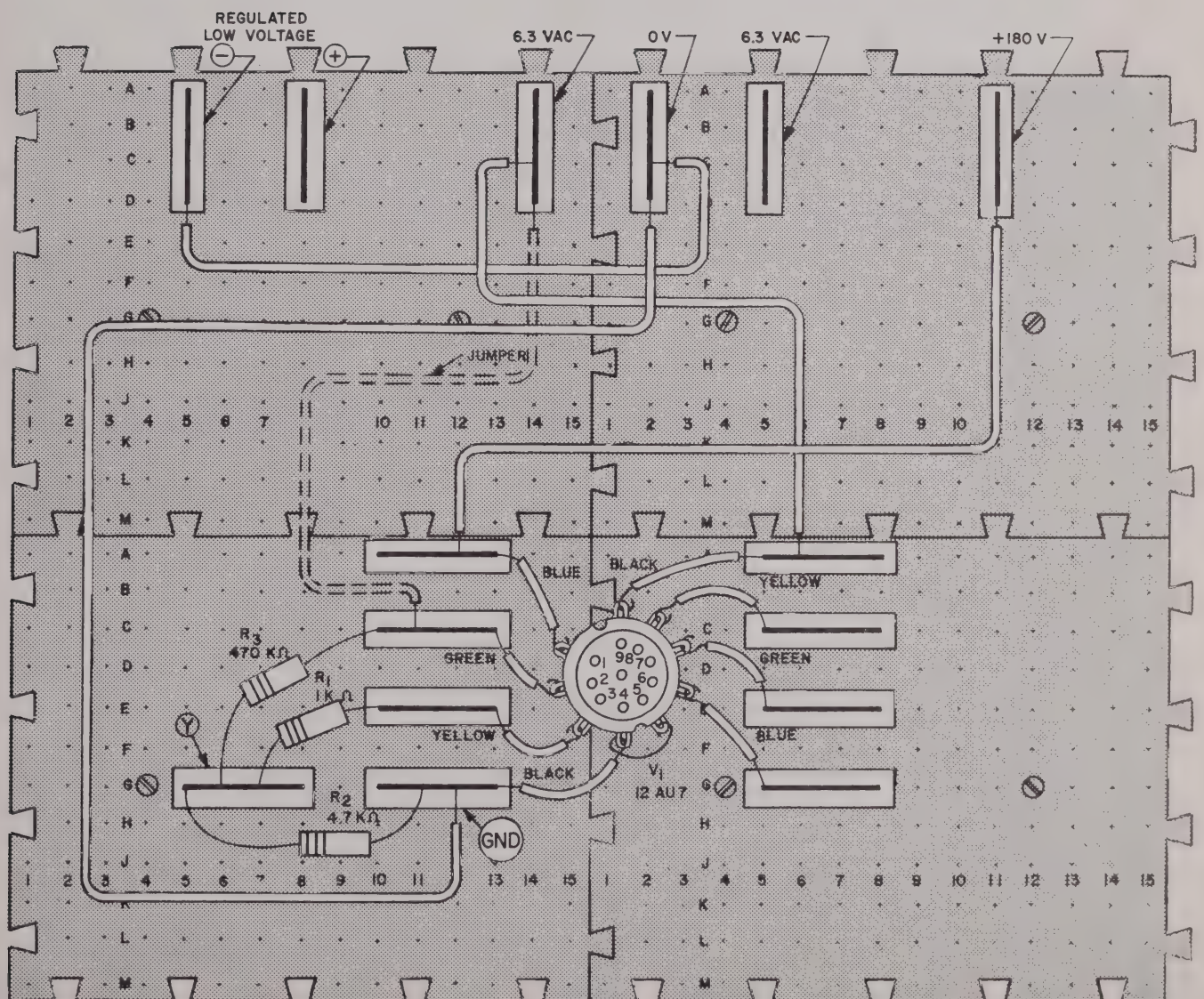


FIGURE 6-2

NOTES



ONE OF THE

BELL & HOWELL SCHOOLS

9504-6A&B
EXAMINATION
CHECK SHEET

NOTICE: To keep our lessons up-to-date, we add material to the texts from time to time, and make occasional changes in the examination questions. Therefore, when checking your answers with this check sheet, look at the code LETTER (A, B, C, etc.) on your examination sheet to determine which of the following groups of answers apply to the lesson which you have.

9504-6B

1. D - A CATHODE FOLLOWER CIRCUIT HAS -- A VOLTAGE GAIN LESS THAN 1.
A cathode follower has a voltage gain a little less than 1 with a higher input impedance and a lower output impedance than the common-cathode stage.
2. B - IN THE CIRCUIT OF FIGURE 6-1, IF THE BOTTOM END OF R_3 IS RETURNED TO GROUND INSTEAD OF TO THE JUNCTION OF R_1 AND R_2 , -- THE GRID-CATHODE VOLTAGE WILL INCREASE.
Moving the lower end of the grid resistor to ground will increase the grid bias, thus reducing plate current.
3. B - THE CATHODE FOLLOWER CIRCUIT OF FIGURE 6-1 IS ALSO REFERRED TO AS A -- GROUND-ED-PLATE AMPLIFIER.
The cathode follower is also called a grounded-plate amplifier since the plate is at ac signal ground by its connection to the power supply.
4. A - A GROUNDED-CATHODE AMPLIFIER HAS -- A LOWER INPUT IMPEDANCE THAN THE CATHODE FOLLOWER.
A common-cathode amplifier has a lower input impedance and a higher output impedance compared to the common plate stage. The grounded-cathode stage has a voltage gain that is much greater than unity.
5. D - WHAT WOULD HAPPEN IN THE CIRCUIT OF FIGURE 6-1 IF A LARGE BYPASS CAPACITOR WERE CONNECTED FROM CATHODE TO GROUND? -- THE VOLTAGE GAIN WOULD DECREASE.
With the cathode bypassed, the ac output signal would be shorted to ground, thus reducing the output signal to almost zero.

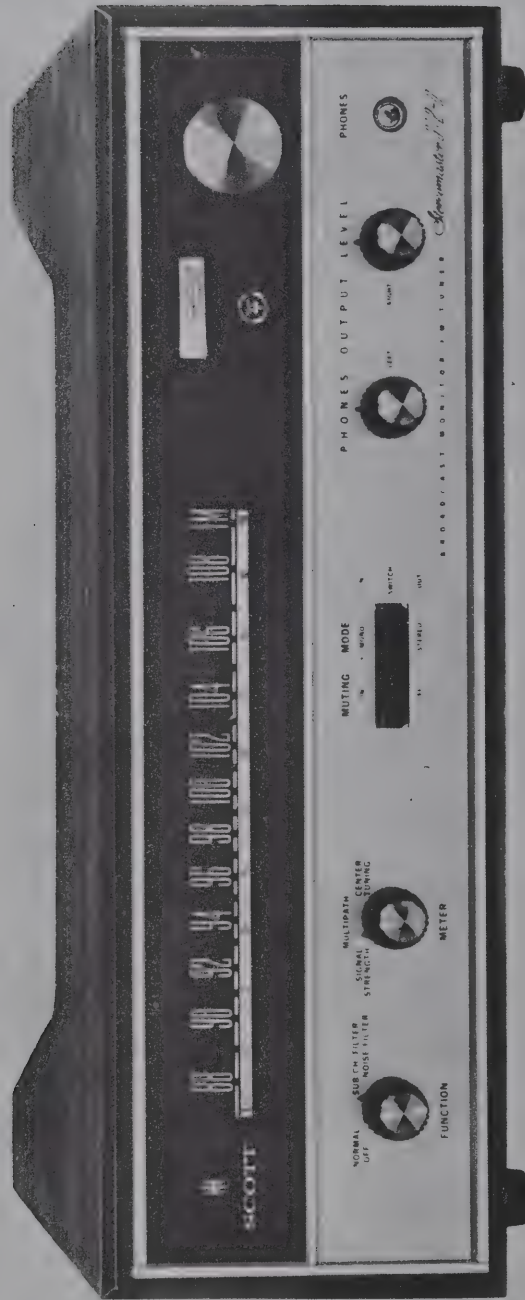
9504-6A

All explanations are the same as for 9504-6B except for that given below.

4. A - A GROUNDED-CATHODE AMPLIFIER HAS -- A HIGH INPUT IMPEDANCE.
A grounded cathode amplifier has a high input impedance and a high output impedance with a high voltage gain.

RLC EFFECTS ON AC

1061



Radio receivers generally employ resonant circuits to select the desired stations.
Courtesy H. H. Scott

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Capacitive Reactance	Page 10
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Impedance of Parallel Circuits	Page 15
Voltage and Current in Series Circuits	Page 19
Practical Methods of Measuring Impedance	Page 22
Appendix — Squares and Square Roots	Page 27

When you get into a tight place and everything goes against you, till it seems as though you could not hold on a minute longer, never give up then, for that is just the place and time the tide will turn.

—Harriet Beecher Stowe

RLC EFFECTS ON AC

It is often easier to understand circuit properties if they can be compared to some familiar mechanical action. For alternating circuits, the actions of a resistor, an inductor and a capacitor are very similar to three common mechanical characteristics of everyday experience.

The RESISTANCE in a circuit is very much like the friction between two surfaces. When a block of wood is pushed back and forth across a smooth surface, it moves easily; that is, little "resistance" is offered. Therefore, it takes only a small pressure to produce a specific speed of motion. To overcome the increased friction of a rough surface, more pressure is required to move the block back and forth at the same speed. The energy used in pushing the block is dissipated as heat, and if the action has been vigorous enough, the heat can be detected by feeling the rubbed surfaces.

The INDUCTANCE in a circuit acts somewhat like the forces involved when pedaling a bicycle. It takes a lot of push or "pumping" to get started, but once the desired speed is reached, the bicycle continues to coast when the pedaling ceases. The energy produced in pedaling is stored up in the bicycle motion and keeps it moving. The motion of the bicycle does not respond immediately to pressure. In fact, maximum speed is reached after the hard pedaling is over. Furthermore, the more quickly we try to change the speed, the more pressure is needed while a slower change requires less pressure.

The CAPACITANCE in a circuit causes an action that is somewhat like pushing or pulling on a spring. It takes very little push at first, but as the spring is compressed further, more pressure is required. Maximum motion occurs during the first part of the push, and maximum pressure is required during the latter part. If the pressure is released, the spring will push back until restored to its original position. The energy stored in the spring compression returns the spring to its normal position.

RESISTANCE IN AC CIRCUITS

In the ac circuit illustrated in Figure 1A, the electric energy of the ac source is consumed and dissipated as heat in resistor R. Current is produced the instant voltage is applied across the resistor, and thus electric energy is consumed without delay. As the voltage increases, the current increases; when the voltage drops, the current decreases; and when the voltage reverses, the current also reverses.

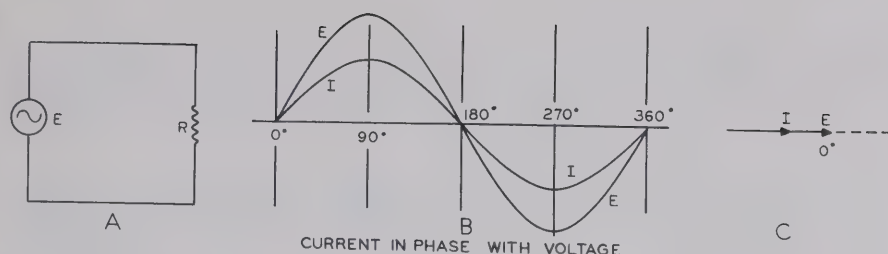
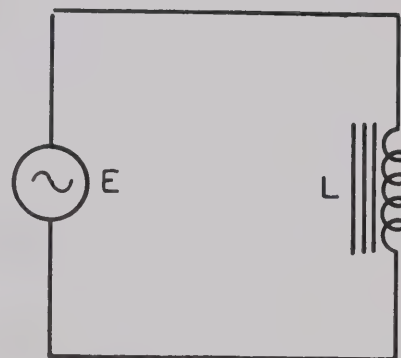


Figure 1

These instantaneous relationships between voltage and current in a resistive ac circuit are shown by the curves of Figure 1B. Since the voltage and current increase and decrease “in step,” always in the same direction at the same instant, they are said to be in phase. In the vector diagram of Figure 1C, this condition is indicated by the fact that the current vector, I , overlaps with and points in the same direction as the voltage vector, E .

INDUCTANCE IN AC CIRCUITS

In the circuit of Figure 2A, resistor R of Figure 1A is replaced by inductor L . Any change of current in an inductor induces a voltage which opposes the change of current which caused it. Thus, while current is increasing, the induced voltage opposes the supply voltage and tends to prevent the increase. When the current is decreasing, the induced voltage reverses polarity and aids the supply voltage to oppose the decrease.


 Figure
2A

According to the laws of induction, the induced voltage is proportional to the rate at which the conductor is cut by magnetic lines of force. In an inductor, the movement or change of the magnetic lines is proportional to the rate of current change. Therefore, the induced voltage is proportional to the rate of current change. The faster the change, the greater the induced voltage. Remember that, regardless of its magnitude, a constant current does not induce a voltage because it creates a steady magnetic field.

As indicated by curve E of Figure 2B, when a sinusoidal alternating voltage is applied across inductor L of Figure 2A, this voltage is constantly changing in magnitude and periodically reversing polarity. Since the current caused by this voltage has a similar change, the induced voltage also is continuous. The action of the induced emf, along with the source voltage, causes the current in the inductor to LAG the source voltage as shown. The curves of Figure 2B show the conditions which would exist in a circuit containing inductance only.

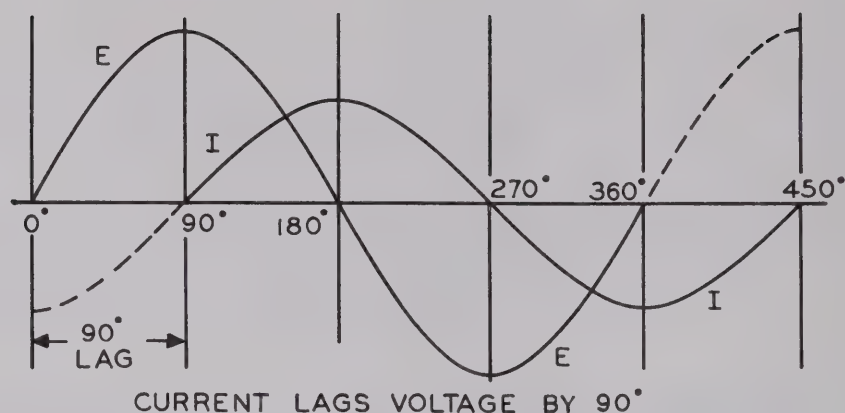


Figure 2B

In Figure 2B the applied voltage, E , rises during the first quarter cycle, but because of the delay caused by the induced voltage, curve I is still going upward at the 90° phase of the source voltage, E . Curve I shows the current increasing rapidly at first, then more and more slowly until it reaches its maximum when the source voltage reaches the 180° phase.

As already mentioned, the induced voltage opposes the applied voltage, and this opposing action prevents the current from rising to maximum the instant the source voltage is applied. The induced voltage is greatest when the current is changing most rapidly. In Figure 2B this condition occurs when I passes through the base line, or zero amplitude. To see this change more clearly, draw a vertical line a few degrees each side of the 270° phase and note that they cross the I curve some distance above and below the base line. Then draw similar lines, equal distances each side of the 180° phase, and note that they both cross the I curve at about the same distance above the base line to indicate only a small change.

Therefore, the highest cemf will be induced when the current is passing through zero because that is the region of greatest change. At its peak value, the current remains constant for an instant and there is no induced emf. In a zero resistance circuit containing inductance, the current will lag 90° behind the voltage. At maximum voltage across the inductor there will be zero current, and at zero supply voltage there is maximum current.

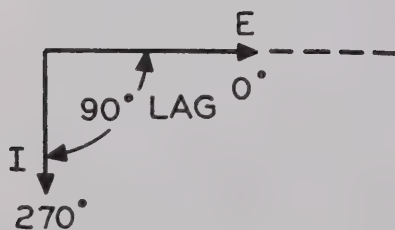


Figure 2C

Reading from left to right across the base line of Figure 2B, the E curve crosses upward at 0° while the current curve crosses upward 90° later. Thus the current "lags" the voltage by 90° . This "out-of-phase" condition is shown by the vector diagram of Figure 2C, where it is assumed that the vectors ro-

tate counterclockwise. The voltage vector E is drawn parallel to the base line to indicate the 0° start or 360° end of a cycle. The current vector I is drawn to correspond with the 270° phase, which lags 360° by 90° .

Actually, there is always resistance as well as inductance in any practical circuit. For example, the connecting wires have resistance. However, this resistance may be very small compared with the effect of the inductance of L . Since all wires offer some resistance to an electric current, it is a practical impossibility to construct a circuit with only inductance. Therefore, the current never lags the voltage by exactly 90° . Depending on the relative values of resistance and inductance, the actual angle of lag is between the 0° of Figure 1 and the 90° of Figure 2.

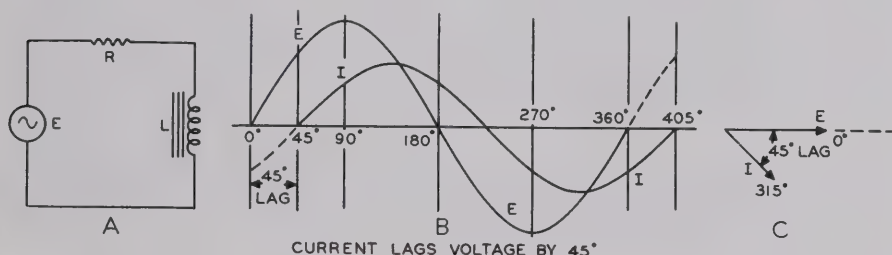


Figure 3

To illustrate this action, in Figure 3 the circuit at A includes resistor R and inductor L with values which cause a current lag of 45° , as indicated by the curves of Figure 3B and the vector diagram of Figure 3C.

INDUCTIVE REACTANCE

All substances oppose electron flow by means of a property called resistance. Those having low resistance are classed as conductors while those with high resistance are considered insulators. Although it only "tends" to prevent CHANGES of current, inductance produces an opposing effect to an alternating current very similar to the opposition of resistance to direct current. This effect is called **INDUCTIVE REACTANCE**. Like resistance, it is measured in ohms.

The factors determining the inductive reactance of an inductor are related as shown by the following expression:

$$X_L = 2\pi fL$$

where: X_L represents the inductive reactance in ohms;

2π is a constant in which the Greek letter π , called "**PI**," represents the quantity 3.1416, and $2 \times \pi = 6.28$, approximately;

f is the frequency of the alternating current in Hz; and

L is the inductance in henries.

As an example, suppose we want to determine the approximate reactance of a filter choke in a power supply. If the inductance, L , is 10 henries and the frequency, f , is 120 Hz, then:

$$\begin{aligned} X_L &= 2\pi fL \\ &= 6.28 \times 120 \times 10 \\ &= 7536 \text{ ohms.} \end{aligned}$$

Often, it is convenient to further abbreviate this expression by representing $2\pi f$ with another Greek letter, ω , called **OMEGA** (lower case). Then, with $2\pi f$ equal to ω , the expression reduces to:

$$X_L = 2\pi fL = \omega L. \quad (1)$$

When the reactance and frequency are known, and it is necessary to determine the inductance, Equation 1 can be rearranged to read:

$$L = \frac{X_L}{2\pi f} = \frac{X_L}{\omega} \quad (1a)$$

As an example of the use of this form of the equation, suppose that a coil has a reactance of 62,800 ohms at a frequency of 1000 kHz, and its inductance is to be determined. Using Equation 1a:

$$\begin{aligned} L &= \frac{X_L}{2\pi f} = \frac{6.28 \times 10^4}{6.28 \times 1 \times 10^6} \\ &= \frac{6.28 \times 10^4 \times 10^{-6}}{6.28} = 1 \times 10^{-2} \\ &= .01 \text{ henry, or 10 millihenries.} \end{aligned}$$

Equation 1 can also be rearranged to determine frequency when the values of inductance and inductive reactance are known, as shown below:

$$f = \frac{X_L}{2\pi L} \quad (1b)$$

CAPACITANCE IN AC CIRCUITS

Figure 4A is similar to Figures 1A and 2A but has a capacitor connected across the ac source. Again, it is assumed that the circuit resistance is zero. ~~A capacitor does not permit the passage of current. Instead, when a capacitor is connected across a source of voltage, electrons flow from the negative terminal of the source to one capacitor plate. This excess of electrons on one plate repels electrons from the other plate, from which electrons flow to the positive terminal of the source. Because the electron flow is in and out, rather than through a capacitor, it is known as a DISPLACEMENT CURRENT.~~

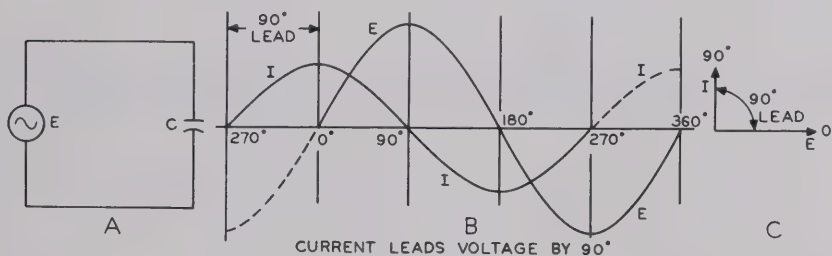


Figure 4

While this action continues the capacitor is said to be charging, and the unbalance of electrons develops a voltage across the plates. Due to the direction of electron flow, the negative plate of the capacitor connects to the negative terminal of the supply. Therefore, the capacitor charges further only when its voltage is exceeded by the source voltage.

In a zero resistance circuit like that of Figure 4A, the voltage across capacitor C equals the source voltage, E, at all times. When the source voltage increases, the displacement current charges the capacitor to increase its voltage also. The faster the increase of source voltage, the greater the displacement current. With no change of source voltage, and equal capacitor voltage, the displacement current is zero.

When the source voltage decreases, the capacitor voltage causes a reversal of displacement current and discharges through the source. The displacement current varies with the rate of decrease of the source voltage to maintain equal capacitor voltage. Therefore, with an ac source as shown in Figure 4A, the capacitor is charging and discharging continuously.

Starting at the 0° phase in the curves of Figure 4B, and assuming that the capacitor is completely discharged, the rapid increase of voltage will cause the charging current to rise almost immediately to its maximum value. Then, as the rate of voltage increase lessens, the charging current will decrease until, at peak voltage, the capacitor is fully charged and the current is zero. This condition is indicated at the 90° phase of source voltage E in Figure 4B.

This action is opposite to that of an inductor because, as shown in Figure 4B, the current rises to maximum **BEFORE** the peak voltage occurs. Therefore, the current LEADS THE VOLTAGE and with nothing but capacitance in a circuit, it will lead the voltage by 90° , as illustrated by the curves of Figure 4B and the vector diagram of Figure 4C.

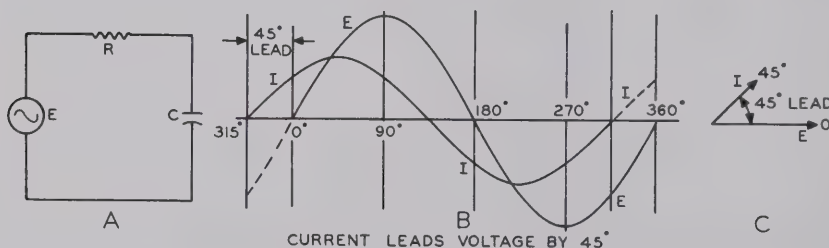


Figure 5

A practical capacitive circuit will always have some resistance, as shown in Figure 5A, and therefore, the angle of lead will be less than 90° . Figure 5B shows the curves, and Figure 5C the vector diagram, for the circuit of Figure 5A, which we will assume contains capacitance and resistance of such values that the current leads the voltage by 45° . Since the current already has a fairly large value at 0° of the voltage curve, we find that the current curve crosses the base line 45° ahead of the voltage curve.

CAPACITIVE REACTANCE

~~The reactance or opposition of a capacitor to the voltage set up by an ac source is known as CAPACITIVE REACTANCE, and like inductive reactance, it is measured in ohms.~~

The following Practice Exercise questions cover the subjects which you have just studied. They are:

RESISTANCE IN AC CIRCUITS

INDUCTANCE IN AC CIRCUITS

INDUCTIVE REACTANCE

CAPACITANCE IN AC CIRCUITS

1. What is the phase relationship between voltage and current in an ac circuit containing only resistance?
2. When examining a vector diagram showing voltage and current, how can you tell if voltage and current are in phase?
3. The counter emf induced in an inductor is maximum when current is (a) maximum, (b) changing at its maximum rate, (c) minimum.
4. Can a practical ac circuit contain only inductance?
5. The maximum rate of change of current with a sinusoidal waveshape occurs when the current is (a) maximum, (b) passing through zero.
6. In an ac circuit containing only inductance, what is the phase relationship between voltage and current?
7. What is the phase relationship between voltage and current in an ac circuit containing both inductance and resistance?
8. In an inductive circuit (a) voltage leads current, (b) voltage lags current, (c) voltage and current are in phase.
9. What is the formula for inductive reactance?

10. What is the value of inductive reactance of a 100 millihenry inductor at a frequency of 1 kHz?
11. Suppose at a particular frequency, a 10 millihenry inductor has a reactance of 9405 ohms. What is the frequency?
12. What is the phase relationship between voltage and current in a purely capacitive circuit?
13. What is the phase relationship between voltage and current in a circuit containing capacitance and resistance?

The factors which determine the capacitive reactance (X_C) of a capacitor are related in the following way:

$$X_C = \frac{1}{2\pi fC} = \frac{1}{\omega C} \quad (2)$$

where: X_C represents capacitive reactance in ohms;

2π numerically is 6.28;

f is the frequency in hertz (cycles per second);

C is the capacitance in farads; and

ω is $2\pi f$.

As an example, suppose that we want to determine the capacitive reactance of a 50 μF capacitor at a frequency of 100 Hz:

$$\begin{aligned} X_C &= \frac{1}{2\pi fC} = \frac{1}{6.28 \times 1 \times 10^2 \times 5 \times 10^{-5}} \\ &= \frac{1}{3.14 \times 10^{-2}} = .3185 \times 10^2 \end{aligned}$$

or 31.9 ohms.

In cases where the capacitive reactance and frequency are known, the capacitance of a capacitor may be determined by rearranging Equation 2 to read:

$$C = \frac{1}{2\pi fX_C} = \frac{1}{\omega X_C} \quad (2a)$$

Thus, if the capacitive reactance is 31.8 ohms and the frequency is 100 Hz, the capacitance is:

$$\begin{aligned} C &= \frac{1}{2\pi fX_C} \\ &= \frac{1}{6.28 \times 1 \times 10^2 \times 3.18 \times 10^1} \\ &= \frac{1}{20 \times 10^3} = \frac{1}{2 \times 10^4} \\ &= .5 \times 10^{-4} \text{ or } 50 \mu\text{F}. \end{aligned}$$

The frequency can also be determined if the value of the capacitance and capacitive reactance are known, as shown below:

$$f = \frac{1}{2\pi X_C C} \quad (2b)$$

IMPEDANCE

So far, we have considered the effect of an ideal inductor or capacitor alone in an ac circuit. There is always some resistance in any practical circuit, and it is necessary to determine what overall opposition the combinations of R and L or R and C have to the applied voltage. Each of these electric quantities offers different types of opposition separately, but together, resistance and reactance "impede" the current, and this opposition is called **IMPEDANCE (Z)**. Impedance is measured in ohms.

Ohm's Law applies to alternating current circuits when the R for resistance is replaced by a Z for impedance. Making this change, the three forms of Ohm's Law for alternating current circuits are:

$$E = IZ \quad (3)$$

$$Z = E/I \quad (3a)$$

$$I = E/Z \quad (3b)$$

where: I = amperes,

E = volts, and

Z = ohms.

IMPEDANCE OF SERIES CIRCUITS

There are several methods by which the impedance of an ac circuit can be determined, but at this time we will use vector diagrams to determine impedance.

In the same way that vectors show the magnitude and direction of current I and voltage E in a circuit, vectors can also be used to represent the magnitude and direction of resistance, reactance, and impedance.

For a circuit like Figure 3 which contains a resistor, R , and an inductor, L , the opposition offered by the resistance is in phase with the voltage while the opposition offered by the inductance is 90° out-of-phase with the voltage. As a specific illustration, we will assume that the resistance of R is 3 ohms, and the reactance of inductor L is 4 ohms. These values and phase angles are represented by the vectors of Figure 6A. The resistance vector is used as the reference vector because resistance does not introduce a phase shift.

To add these two vectors, lines are drawn parallel to the R and X_L vectors, as shown in Figure 6B. The resultant vector represents the circuit impedance, which is the vector sum of R and X_L . Remember, out-of-phase voltages, currents, or reactances must be added vectorially. The length of the resultant vector in Figure 6B is 5 units, which represents an impedance of 5 ohms. The phase angle of the impedance vector can be measured with respect to the reference line. In this case, the angle is approximately 53° .

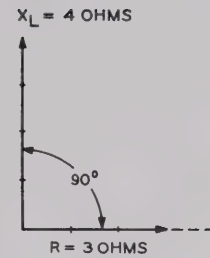
In a capacitive circuit like that of Figure 5A, the opposition offered by the resistance is in phase with the voltage, while the opposition of the capacitor is 90° out-of-phase. Let's assume a resistance of 3 ohms and a capacitive reactance of 4 ohms.

These values and phase angles are indicated by the vector diagram of Figure 7A. Notice that the capacitive reactance vector is 90° out-of-phase with the resistance but is now drawn downward instead of upward. It has become conventional to avoid confusion between an inductive reactance and a capacitive reactance by always DRAWING THE INDUCTIVE REACTANCES UPWARD and the CAPACITIVE REACTANCES DOWNWARD.

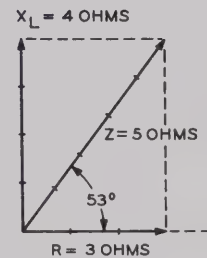
Again, the vectors are added in the same manner as was done in Figure 6. Lines are drawn parallel to the X_C and R vectors to determine the resultant vector. The resultant vector is the circuit impedance, the vector sum of X_C and R . We find that the resultant impedance in Figure 7B is 5 ohms and capacitive, as the vector points between the resistance and capacitance vectors.

From these series circuit examples, we can observe that if the inductance vector is always pointed upward, the resistance vector to the right, and the capacitance vector downward, the resultant vector not only gives the value of impedance, but also indicates whether the circuit is inductive or capacitive.

The impedance for a series circuit can also be found mathematically by employing the vector sum formula, since R and X_L or X_C are 90° apart.

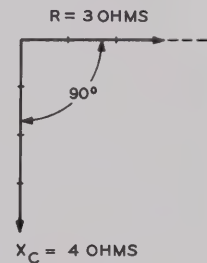


A

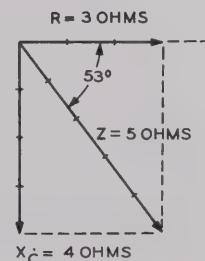


B

Figure 6



A



B

Figure 7

This process can produce more exact answers since the inherent inaccuracies of the graphical solution are eliminated.

When using the vector sum formula, the square root of a number must be determined. The appendix at the end of this lesson gives a square and square root table as well as instructions for its use.

The impedance of a series RL circuit is found arithmetically by use of the vector sum formula:

$$Z = \sqrt{R^2 + X_L^2} \quad (4)$$

For the particular example of Figure 6, the series RL circuit has a resistance of 3 ohms and an inductive reactance of 4 ohms. The impedance is:

$$Z = \sqrt{R^2 + X_L^2} = \sqrt{3^2 + 4^2}$$

$$Z = \sqrt{9 + 16} = \sqrt{25} \text{ or } 5 \text{ ohms.}$$

A series RC circuit is solved exactly the same way as an RL circuit except that the X_C vector points downward to distinguish it from an X_L vector. The vector diagram and data for such a circuit is shown in Figure 7B and the impedance equation is:

$$Z = \sqrt{R^2 + X_C^2} \quad (5)$$

In this case, $R = 3$ ohms, $X_C = 4$ ohms and the impedance is:

$$Z = \sqrt{3^2 + 4^2} = \sqrt{9 + 16}$$

$$= \sqrt{25} = 5 \text{ ohms.}$$

A more general equation for RL or RC series circuits is:

$$\left(Z = \sqrt{R^2 + X^2} \right) \quad (6)$$

in which X replaces X_L or X_C without using the subscript identifying the part.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

CAPACITIVE REACTANCE

IMPEDANCE

IMPEDANCE OF SERIES CIRCUITS

14. What is the formula for capacitive reactance?

15. What is the value of capacitive reactance of a 100 pF capacitor at 1 MHz?

16. At what frequency will a .01 μF capacitor have a reactance of 1 k Ω ?

17. The impedance of R and X_L in a series RL circuit is their (a) arithmetic sum, (b) vector sum.

18. Using vectors, determine the impedance of a series RL circuit where $R = 8$ ohms and $X_L = 6$ ohms.

19. What vector is used as the reference vector in a vector diagram for a series RL or RC circuit?

20. If the angle of the impedance vector is between 0 and 90° , the circuit is _____, and if the angle of the impedance vector is between 270° and 360° , the circuit is _____.
21. What are the vector sum formulas for determining the total impedance of series RC and RL circuits?
22. Using the vector sum formula, what is the impedance of a series RL circuit where $R = 100$ ohms and $X_L = 300$ ohms?

IMPEDANCE OF PARALLEL CIRCUITS

The conventional formulas used for parallel circuit resistance cannot be used to determine the impedance of a parallel circuit. Remember, voltage and current are not in phase in circuits having inductance or capacitance. In a series circuit, the impedance can be found by taking the vector sum of R and X_C or R and X_L . The vector sum process cannot be readily applied to the product over the sum relationship used for parallel circuits. Instead, impedance can be found indirectly by determining total circuit current. Since the total current is the sum of the branch circuits, the total current in a parallel RC or RL circuit is the vector sum of the branch currents.

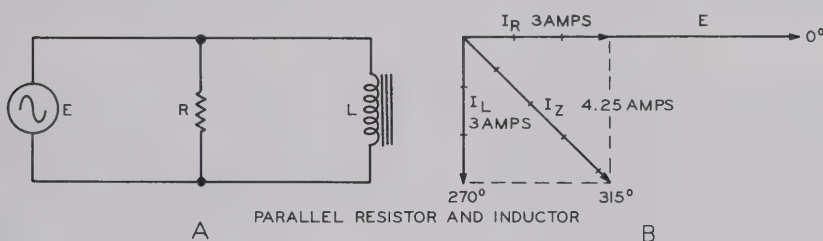


Figure 8

Figure 8A shows a parallel circuit consisting of a resistor and an inductor. The E vector is used as the 0° reference, and may be drawn to any convenient length, since the same voltage is applied to each component in a parallel circuit. The current, I_R , in the resistive branch, R , is in phase with the applied voltage, E , but the current, I_L , in the inductive branch, L , lags the voltage by 90° . These phase relationships are indicated by the vector diagram of Figure 8B. Notice that the I_R vector is drawn on top of and in the same direction as the E vector.

With vectors of the proper length and direction for each of the currents, they may be added as previously explained. The resultant vector, I_Z , will point in a direction between 270° and 0° , depending on the relative magnitudes of the resistive and inductive currents. (Remember, current lags voltage in an inductive circuit.)

If the resistance is equal to the inductive reactance, then the resultant current, I_Z , LAGS the applied voltage by 45° . To illustrate such a condition, for Figure 8 we will assume that R has a resistance of 8 ohms, L has an inductive reactance of 8 ohms, and the applied voltage is 24 volts.

The branch currents are:

$$\begin{aligned} I_R &= \frac{E}{R} \\ &= \frac{24}{8} = 3 \text{ amperes.} \end{aligned}$$

$$\begin{aligned} I_L &= \frac{E}{X_L} \\ &= \frac{24}{8} = 3 \text{ amperes.} \end{aligned}$$

The I_R vector is drawn 3 units long in the 0° direction to represent the resistive current, and vector I_L is also drawn 3 units long in the 270° direction, to represent the inductive current lagging the reference voltage by 90° . By using the technique described for Figures 6 and 7, the resultant vector, I_z , will be found to be 4.25 units long in the direction of 315° , or lagging the source voltage by 45° . This angle can be measured by a protractor. Since 1 unit represents 1 ampere, 4.25 units represent 4.25 amperes. The resulting impedance is:

$$\begin{aligned} Z &= \frac{E}{I_z} \\ &= \frac{24}{4.25} = 5.65 \text{ ohms.} \end{aligned}$$

Figure 9A shows a parallel circuit consisting of a resistor and a capacitor. Again, the E vector is used as the reference. The impedance can be determined by the same methods as used for a parallel inductor and resistor combination. The difference will be in the phase relationship between current and voltage.

The resistive current vector, I_R , is drawn in phase with the applied voltage in the 0° direction, and the capacitive current vector, I_C , is drawn leading the reference vector by 90° . (Remember, voltage lags current in a capacitive circuit.) With the same values of resistance and reactance as were used for the example of Figure 8, the resultant current, I_z , and the impedance, Z , will be the same. The difference is that the resultant current vector, I_z , leads the source voltage by 45° .

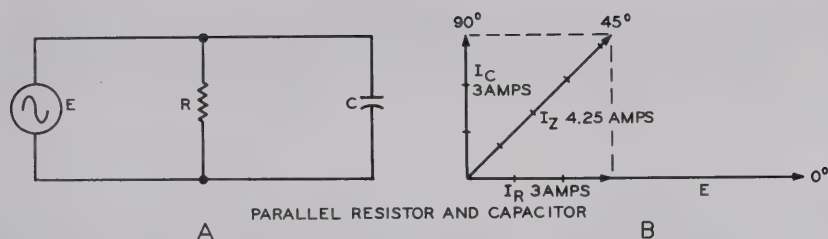


Figure 9

The vector sum formula can also be used to determine the impedance of a parallel RC or RL circuit. The vector sum formula is used to determine the total circuit current. The circuit impedance is then found in the same manner as when the graphical vector sum procedure is employed.

The value of I_Z is:

$$I_Z = \sqrt{I_R^2 + I_L^2} \quad (7)$$

In the diagram of Figure 8B, I_R and I_L are each 3 amperes, and replacing the symbols with the currents they represent, the equation can be solved:

$$\begin{aligned} I_Z &= \sqrt{3^2 + 3^2} \\ &= \sqrt{9 + 9} \\ &= \sqrt{18} = 4.243 \text{ amps.} \end{aligned}$$

In most cases this current can be "rounded off" to:

$$I_Z = 4.24 \text{ amperes}$$

which compares favorably with the measured vector I_Z as 4.25 amperes. The calculated impedance is then:

$$\begin{aligned} Z &= \frac{E}{I_Z} \\ &= \frac{24}{4.24} \\ &= 5.66 \text{ ohms.} \end{aligned}$$

Notice that this net or resultant impedance, Z , is less than the 8 ohms resistance of the R branch, and less than the 8 ohms inductive reactance (X_L) of the L branch. This example again proves the general rule for a parallel circuit:

**THE RESULTANT OPPOSITION TO THE ACTING
VOLTAGE IS LESS THAN THE SMALLEST OF
ANY OF ITS BRANCHES.**

From Equation 1a, and assuming a frequency of 60 Hz, the inductance L of the circuit is:

$$\begin{aligned} L &= \frac{X_L}{2\pi f} \\ &= \frac{8}{6.28 \times 60} \\ &= \frac{8}{377} = .0212 \text{ henry.} \end{aligned}$$

L CANNOT be compared with Z because Z is measured in ohms and L in henries. Numerically, though, Z is larger than L . The current in the L branch is determined from:

$$I_L = \frac{E}{X_L}$$

$$\text{Also, } I_R = \frac{E}{R}$$

As explained, I_R and I_L must be combined vectorially, NOT ADDED, to find I_Z . Finally, the impedance of an RL circuit is found from the equation:

$$Z = \frac{E}{I_Z}$$

The vector sum formula can also be used in the RC circuit of Figure 9. In this case, I_C takes the place of I_L in the vector sum formula:

$$I_Z = \sqrt{I_R^2 + I_C^2} \quad (8)$$

Again, $I_Z = 4.24$ amperes and $Z = 5.66$ ohms (approximately).

In the above explanations we followed fundamental principles. For parallel circuits, the source voltage is applied across each branch. However, to find the total current, due to the effects of reactance, the branch currents were added vectorially in order to determine the total current. For conditions of either a capacitor or an inductor in parallel with a resistor, I_X replaces I_C or I_L . Thus, as a general equation:

$$I_Z = \sqrt{I_R^2 + I_X^2} \quad (9)$$

Also, due to the effects of reactance, the total or equivalent opposition to the current is the impedance of the circuit.

The relationships of voltage and current in parallel circuits are shown in Figure 10.

VOLTAGE AND CURRENT IN SERIES CIRCUITS

The impedance of a parallel circuit is found indirectly by first determining total circuit current. A similar procedure can be employed in series circuits by determining total circuit voltage and current. The impedance is then equal to the total circuit voltage divided by the circuit current.

The current is the same in all parts of a dc series circuit at any instant, but the voltage drops across the different components vary with their resistances. The total circuit resistance is equal to the sum of the separate resistances, and the sum of the separate voltage drops is equal to the applied, or source, voltage.

In general, these conditions hold true for ac series circuits, but the effects of reactance make it necessary to employ vector addition to determine impedances and voltage drops. For vector diagrams of ac series circuits, the current is used as the reference because it is the same in all parts of the circuit.

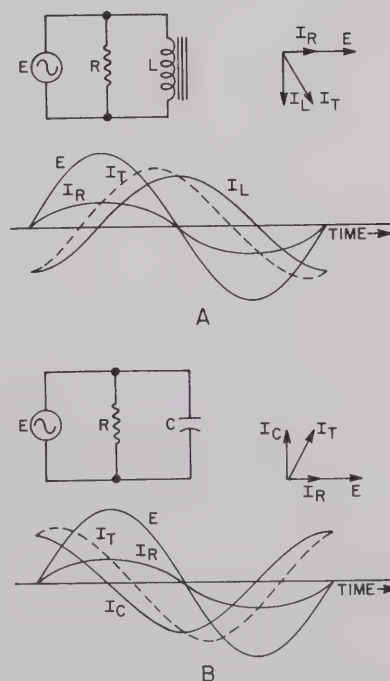


Figure 10

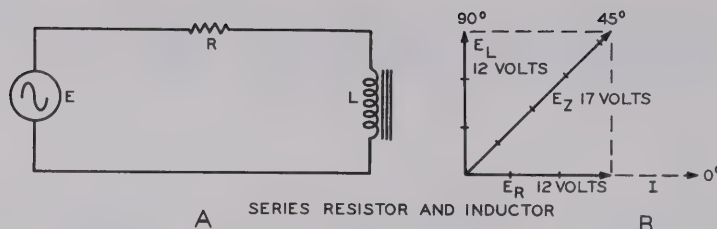


Figure 11

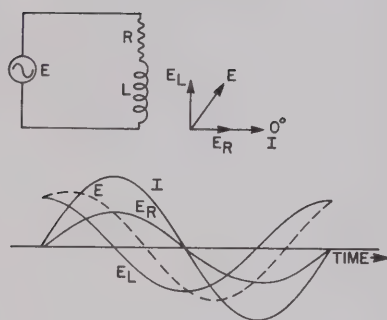


Figure 12

Figure 11A shows a series circuit which includes a resistor, R , an inductor, L , and an alternating voltage source, E . Using the circuit current as the reference, in Figure 11B, vector I is drawn in a horizontal direction and labeled 0° . Since the voltage drop across a resistor is in phase with the current through it, vector E_R also is drawn in the 0° direction. Finally, since the current through an inductor lags the voltage across it by 90° , vector E_L is drawn leading the reference current by 90° . Figure 12 shows the relationships of voltages and current in series circuits.

Just as the impedance of the parallel circuit is found by dividing the applied voltage, E , by the resulting current, I_Z , the impedance of a series circuit can be found by dividing the circuit voltage, E_Z , by the circuit current, I .

Let's use the graphic vector addition method first, and assume that R has a resistance of 6 ohms, L has an inductive reactance of 6 ohms and the series circuit current, I , is 2 amperes. The voltage drop across each component is:

$$\begin{aligned} E_R &= I \times R \\ &= 2 \times 6 = 12 \text{ volts.} \end{aligned}$$

$$\begin{aligned} E_L &= I \times X_L \\ &= 2 \times 6 = 12 \text{ volts.} \end{aligned}$$

Selecting convenient lengths for drawing the vectors, let one unit equal 4 volts. Then 12 volts is 3 units long. In Figure 11, the 0° I vector can be drawn to a suitable length which exceeds the resistor voltage vector.

The E_R vector, 3 units long, is drawn in the 0° direction to represent the resistive voltage, and the E_L vector, also 3 units long, is drawn in the 90° direction as the inductive voltage, leading the reference current vector, I .

Using the same method described for vector addition for Figures 6 and 7, the resultant voltage vector, E_Z , is approximately 4.25 units in length in the 45° direction. Since 1 unit = 4 volts, $4.25 \times 4 = 17$ volts. Thus, $E_Z = 17$ volts approximately, and it leads the current by 45° . This is the same as saying that the current lags the voltage, since the circuit is inductive in nature. In a series RL circuit, the total, or circuit, voltage, E_Z , is determined from the equation:

$$E_Z = \sqrt{E_R^2 + E_L^2} \quad (10)$$

Here, in the notation E_Z , the letter E represents the applied circuit voltage, and the subscript Z indicates that the voltages E_R and E_L are to be combined vectorially. Substituting the voltage drops of the example into the equation,

$$\begin{aligned} E_Z &= \sqrt{12^2 + 12^2} \\ &= \sqrt{144 + 144} \\ &= \sqrt{288} \\ &= 16.98 \text{ or } 17 \text{ volts approximately.} \end{aligned}$$

The circuit impedance is:

$$Z = \frac{E_Z}{I_Z} = \frac{17}{2} = 8.5 \text{ ohms.}$$

Notice that the "total impedance" is greater than either the resistance, R, or inductive reactance, X_L , of 6 ohms each. This is a characteristic of series circuits.

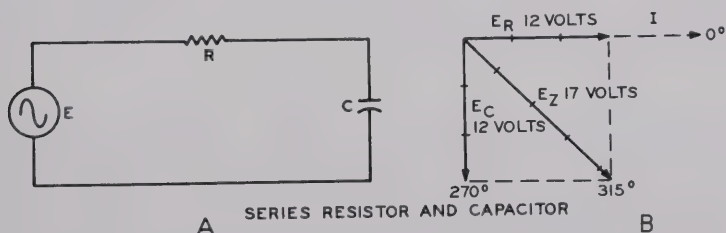


Figure 13

Figure 13A shows a series circuit of a resistor, R , and a capacitor, C . Again, current I is the reference vector and vectors E_C , E_R , and the resultant vector E_Z , are as shown in Figure 13B. Although the I vector leads the E_C vector by 90° , E_C is drawn at the 270° phase. With the same values of resistance, reactance and current as used for the illustration of Figure 11, the voltage and impedance will be exactly the same, but in this case the current leads the voltage by 45° since the voltage is at the 315° phase. Briefly then, the previous equation contains an " E_C^2 " instead of E_L^2 and:

$$E_Z = \sqrt{E_R^2 + E_C^2} \quad (11)$$

Again, $Z = 8.5$ ohms (approximately).

To cover conditions when a capacitor or inductor is acting in series with a resistor, E_x may be used for either E_C or E_L . Thus, in a general equation:

$$E_Z = \sqrt{E_R^2 + E_x^2} \quad (12)$$

PRACTICAL METHODS OF MEASURING IMPEDANCE

Why is impedance important? Because many of the components such as chokes, capacitors, transformers, loudspeakers, tuned circuits, filters, antennas and transmission lines have impedance characteristics when in ac circuits, and knowledge of how they function gives a clue to faults in electronic equipment containing them. Although impedance measurements probably won't be made as often as resistance measurements in service and maintenance procedures, Figure 14 illustrates a voltmeter-ammeter impedance-measuring method.

The ac ammeter is connected in series with a block, Z , which represents the connections to an unknown impedance, and the combination is connected to an ac source of voltage, E , that has a specific frequency. The ac voltmeter is connected as shown and forms a parallel circuit with the load. Therefore, it preferably is an electronic meter with a high input impedance so that it will not affect the Z measurement. As explained in this lesson, the impedance (in ohms) of an ac circuit is:

$$Z = \frac{E}{I}$$

where: I is in amperes and

E is in volts.

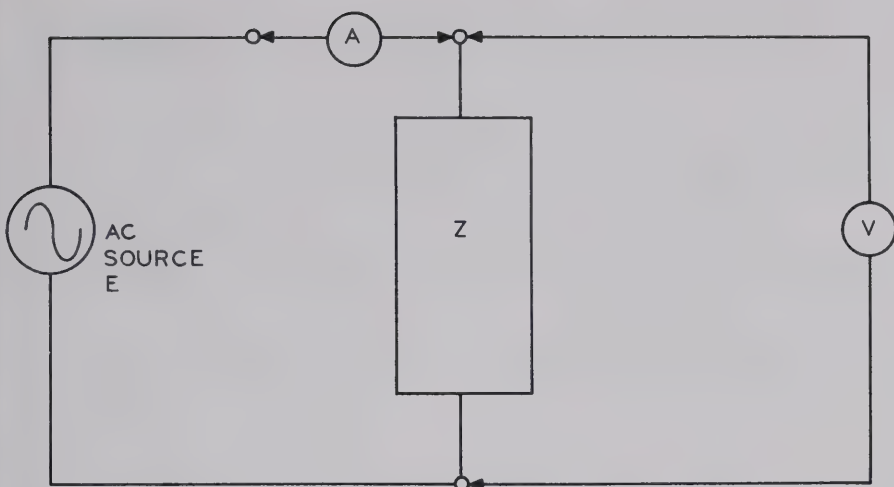


Figure 14

The meter indicating scales for I and E must be the same — either rms, peak, or average. For example, if $I = .05$ ampere, and $E = 50$ volts, the impedance will equal

$$Z = \frac{E}{I}$$

$$= \frac{50}{.05}$$

$$= 1000 \text{ ohms.}$$

Another impedance-measuring method is shown in Figure 15. It does not require the measurement of alternating current. The circuit arrangement takes the form of a "bridge," and adjustments must be performed before a recording is obtained.

The unknown impedance, Z , which may be a capacitor, coil or some combination of inductance, capacitance, and resistance, is connected in series with a calibrated rheostat (variable resistor) and a source of ac voltage. The variable resistor scale reads directly in ohms. The source voltage forces a current through the unknown impedance and the variable resistor in series, causing voltage drops E_Z and E_R across the separate components.

RLC EFFECTS ON AC

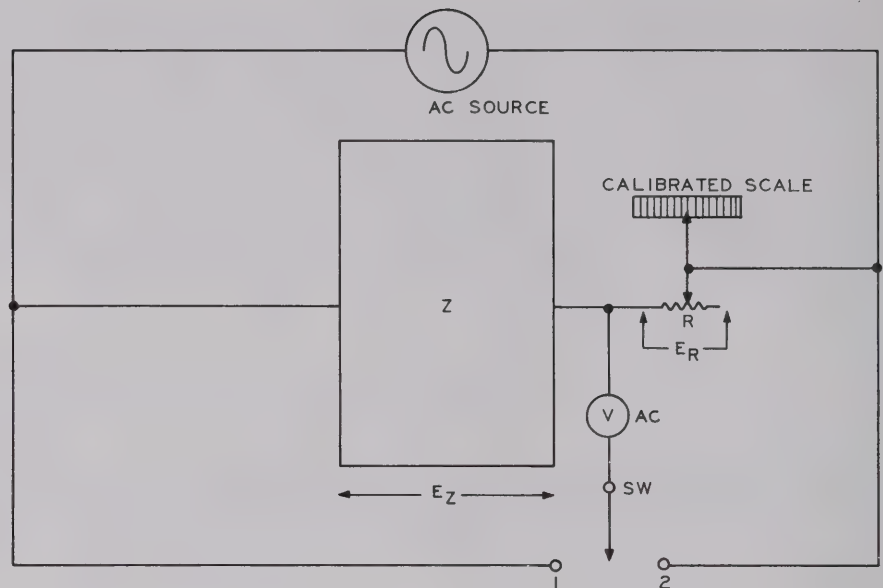


Figure 15

With the voltmeter (preferably a high impedance type) connected to the switch as shown, it is possible, by “flipping” the switch from position 1 to position 2, to measure the voltage across Z and then across a portion of R , depending upon the variable arm position. In switch position 1 the E_Z voltage is measured, and in position 2 the E_R voltage is measured. If E_R differs from E_Z , then R is varied until $E_R = E_Z$. This procedure may require that the switch be thrown from one position to the other several times. When balance is achieved, the scale marking of the indicator or R is noted. This $R = Z$ indication is the impedance of the component at the frequency of the source voltage. A convenient source voltage is that of the ordinary house lighting circuit — 60 Hz. Both of the methods of measurement that were described require that the frequency of the source voltage be known. If the impedance of other frequencies must be determined, an electronic sinewave generator which will produce an output at the desired frequency must be used in place of the 60-Hz source.

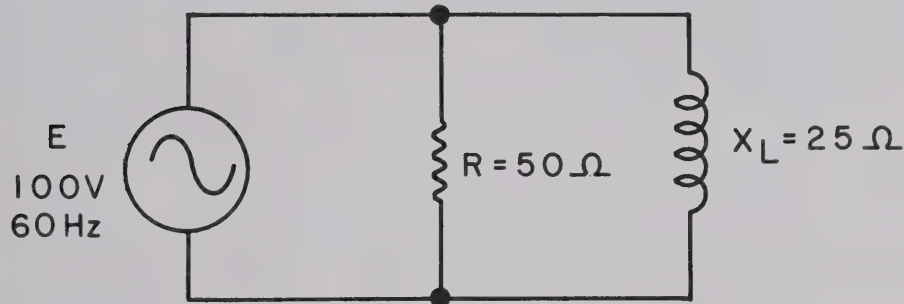
The following Practice Exercise questions cover the subjects which you have just studied. They are:

IMPEDANCE OF PARALLEL CIRCUITS

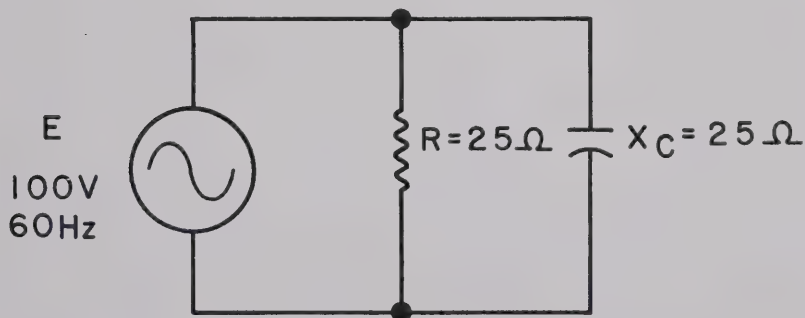
VOLTAGE AND CURRENT IN SERIES CIRCUITS

PRACTICAL METHODS OF MEASURING IMPEDANCE

23. Explain how total impedance is found in a parallel circuit by using vectors.
24. Determine the total impedance in the following circuit by using vectors.

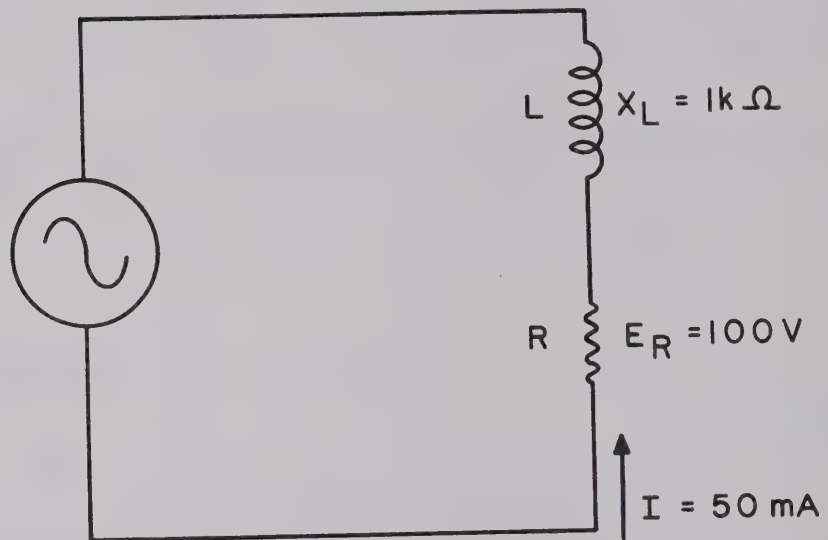


25. Is the phase relation between voltage and current in series and parallel RC circuits the same?
26. Determine the total circuit current in the following circuit by using vectors.



27. How is the vector sum formula employed in determining the impedance of a parallel RC or RL circuit?

28. Using the vector sum formula, what is the impedance of a parallel RC circuit where $E = 150$ volts, $X_C = 300$ ohms and $R = 600$ ohms?
29. How is the impedance of a series RL or RC circuit found by employing circuit voltage and circuit current?
30. What is the impedance of the circuit shown below?



31. How is the impedance found in the circuit of Figure 14?

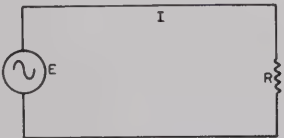
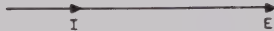
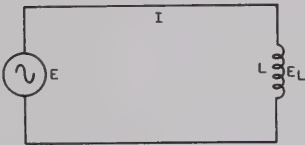
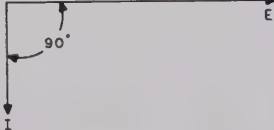
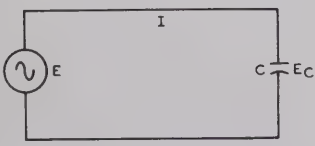
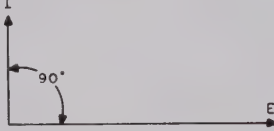
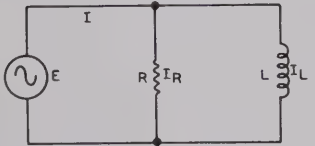
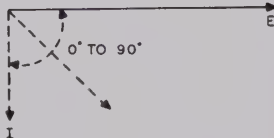
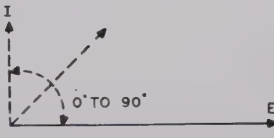
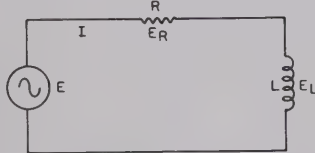
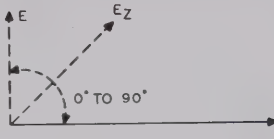
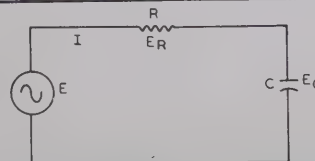
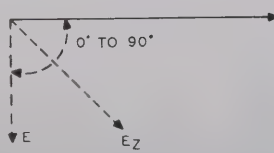
SUMMARY

To help you remember the important points in this lesson, a chart is included at the end of this summary. In a sense, this chart is a summary of the major points of the entire lesson.

For example, if you wanted to quickly review the essential characteristics of an ac circuit containing a resistor R in series with an inductor L , you can readily locate the circuit arrangement in columns 1 or 2. Column 3 gives the phase angle relationship, and column 4 indicates the associated vector diagram. The most useful equations are given in column 5, whereas additional general comments appear in column 6.

You may have wondered why parallel and series RLC combinations were not included in this lesson. They haven't been forgotten. However, they are best explained in the next lesson where we tell you how changes of frequency affect ac circuits containing inductance and capacitance, and their combinations with resistance.

SUMMARY CHART

Nature of Circuit	Components Employed	Phase Angle Between E and I	Vector Diagram	Most Useful Equations	General Comments
	R only	E and I in phase		$R = \frac{E}{I}$	applied voltage $E = IR$
	L only	I lags E 90°		$X_L = 2\pi fL$ $X_L = \frac{E_L}{I}$	The induced voltage action causes the circuit current to lag the voltage
	C only	I leads E 90°		$X_C = \frac{1}{2\pi fC}$ $X_C = \frac{E_C}{I}$	Due to the very rapid charge of a capacitor, the circuit current leads the voltage.
	R and L in parallel	I lags E between 0° and 90°		$I_Z = \sqrt{I_R^2 + I_L^2}$ $Z = \frac{E}{I_Z}$	The I_R vector is in phase with the reference vector E. The I_L vector lags the reference vector by 90°. Z in ohms is less than the smaller of R or X_L .
	R and C in parallel	I leads E between 0° and 90°		$I_Z = \sqrt{I_R^2 + I_C^2}$ $Z = \frac{E}{I_Z}$	The I_R vector is in phase with the reference vector E. The I_C vector leads the reference vector by 90°. Z in ohms is less than the smaller of R or X_C .
	R and L in series	I lags E between 0° and 90°		$E_Z = \sqrt{E_R^2 + E_L^2}$ $Z = \frac{E_Z}{I}$	The E_R vector is in phase with the reference vector I. The E_L vector leads the reference vector by 90°. Z in ohms is greater than the larger of R or X_L .
	R and C in series	I leads E between 0° and 90°		$E_Z = \sqrt{E_R^2 + E_C^2}$ $Z = \frac{E_Z}{I}$	The E_R vector is in phase with the reference vector I. The E_C vector lags the reference vector by 90°. Z in ohms is greater than the larger of R or X_C .

APPENDIX

SQUARES AND SQUARE ROOTS

The following table is given as an aid in working out problems involving squares and square roots. The square or square root of any whole number from 1 to 100 can be found by means of the first three columns, headed n , n^2 , and $\sqrt{n}$.

As an example, to find the square of the number 6, we first locate 6 in the n column. Then, moving across to the n^2 column, we find the number 36, which is equal to 6^2 .

To find the square root of 49, we first locate 49 in the n column. Then, moving to the right to the $\sqrt{n}$ column, we find the number 7, which is equal to $\sqrt{49}$.

The fourth column, headed $\sqrt{10n}$, permits finding the square root of every tenth number from 10 to 1,000. As an example, suppose we desire to find the square root of 650. Dividing 650 by 10, we obtain 65. That is, 650 is equal to 10×65 . Accordingly, we can substitute the number 65 for n in the expression $\sqrt{10n}$. To find the root, we locate 65 in the n column, then move across to the $\sqrt{10n}$ column where we find the number 25.495, which is equal to $\sqrt{650}$.

Finally, the numbers in the n column are the square roots, respectively, of the particular numbers listed in the n^2 column. For example, to find the square root of 625, we first locate this number in the n^2 column, then move left to the n column to obtain 25, which is the square root of 625.

APPENDIX (Continued)

n	n ²	$\sqrt{n}$	$\sqrt{10n}$	n	n ²	$\sqrt{n}$	$\sqrt{10n}$
1	1	1.000	3.162	51	2,601	7.141	22.583
2	4	1.414	4.472	52	2,704	7.211	22.804
3	9	1.732	5.477	53	2,809	7.280	23.022
4	16	2.000	6.325	54	2,916	7.348	23.238
5	25	2.236	7.071	55	3,025	7.416	23.452
6	36	2.449	7.746	56	3,136	7.483	23.664
7	49	2.646	8.367	57	3,249	7.550	23.875
8	64	2.828	8.944	58	3,364	7.616	24.083
9	81	3.000	9.487	59	3,481	7.681	24.290
10	100	3.162	10.000	60	3,600	7.746	24.495
11	121	3.317	10.488	61	3,721	7.810	24.698
12	144	3.464	10.954	62	3,844	7.874	24.900
13	169	3.606	11.402	63	3,969	7.937	25.100
14	196	3.742	11.832	64	4,096	8.000	25.298
15	225	3.873	12.247	65	4,225	8.062	25.495
16	256	4.000	12.649	66	4,356	8.124	25.690
17	289	4.123	13.038	67	4,489	8.185	25.884
18	324	4.243	13.416	68	4,624	8.246	26.077
19	361	4.359	13.784	69	4,761	8.307	26.268
20	400	4.472	14.142	70	4,900	8.367	26.458
21	441	4.583	14.491	71	5,041	8.426	26.646
22	484	4.690	14.832	72	5,184	8.485	26.833
23	529	4.796	15.166	73	5,329	8.544	27.019
24	576	4.899	15.492	74	5,476	8.602	27.203
25	625	5.000	15.811	75	5,625	8.660	27.386
26	676	5.099	16.124	76	5,776	8.718	27.568
27	729	5.196	16.432	77	5,929	8.775	27.749
28	784	5.292	16.733	78	6,084	8.832	27.928
29	841	5.385	17.029	79	6,241	8.888	28.107
30	900	5.477	17.321	80	6,400	8.944	28.284
31	961	5.568	17.607	81	6,561	9.000	28.461
32	1,024	5.657	17.889	82	6,724	9.055	28.636
33	1,089	5.745	18.166	83	6,889	9.110	28.810
34	1,156	5.831	18.439	84	7,056	9.165	28.983
35	1,225	5.916	18.708	85	7,225	9.220	29.155
36	1,296	6.000	18.974	86	7,396	9.274	29.326
37	1,369	6.083	19.235	87	7,569	9.327	29.496
38	1,444	6.164	19.494	88	7,744	9.381	29.665
39	1,521	6.245	19.748	89	7,921	9.434	29.833
40	1,600	6.325	20.000	90	8,100	9.487	30.000
41	1,681	6.403	20.248	91	8,281	9.539	30.166
42	1,764	6.481	20.494	92	8,464	9.592	30.332
43	1,849	6.557	20.736	93	8,649	9.644	30.496
44	1,936	6.633	20.976	94	8,836	9.695	30.659
45	2,025	6.708	21.213	95	9,025	9.747	30.822
46	2,116	6.782	21.448	96	9,216	9.798	30.984
47	2,209	6.856	21.679	97	9,409	9.849	31.145
48	2,304	6.928	21.909	98	9,604	9.899	31.305
49	2,401	7.000	22.136	99	9,801	9.950	31.464
50	2,500	7.071	22.361	100	10,000	10.000	31.623

IMPORTANT DEFINITIONS

CAPACITIVE REACTANCE (X_C) — The opposition that an alternating current experiences due to the capacitive effect that exists in a circuit.

INDUCTIVE REACTANCE (X_L) — The opposition that an alternating current experiences due to the inductive counter emf that is developed in a circuit.

IMPEDANCE (Z) — The total opposition to current in an ac circuit. The vector sum of resistance and reactance. It is measured in ohms. Numerically, $Z = \sqrt{R^2 + X^2}$

OMEGA (ω) — A Greek letter. Used to designate the term $2\pi f$.

PI (π) — A Greek letter. Used to designate 3.1416.

ESSENTIAL SYMBOLS AND EQUATIONS

C	Capacitance (farads)
E_R	Voltage across resistor (volts)
E_X	Voltage across reactance (volts)
E_Z	Voltage across impedance (volts)
f	Frequency (hertz, or cycles/second)
I_C	Current in capacitor (amperes)
I_L	Current in inductor (amperes)
I_R	Current in resistor (amperes)
I_X	Current in reactance (amperes)
I_Z	Circuit current (amperes)
L	Inductance (henries)
X	Reactance (ohms)
X_C	Capacitive reactance (ohms)
X_L	Inductive reactance (ohms)
Z	Impedance (ohms)
π	Pi (3.1416)
ω	Omega ($2\pi f$)

$$X_L = 2\pi fL = \omega L \quad (1)$$

$$L = \frac{X_L}{2\pi f} = \frac{X_L}{\omega} \quad (1a)$$

$$f = \frac{X_L}{2\pi L} \quad (1b)$$

$$X_C = \frac{1}{2\pi fC} = \frac{1}{\omega C} \quad (2)$$

ESSENTIAL SYMBOLS AND EQUATIONS (Continued)

$$C = \frac{1}{2\pi f X_C} = \frac{1}{\omega X_C} \quad (2a)$$

$$f = \frac{1}{2\pi X_C C} \quad (2b)$$

$$E = IZ \quad (3)$$

$$Z = E/I \quad (3a)$$

$$I = E/Z \quad (3b)$$

$$Z = \sqrt{R^2 + X_L^2} \quad (4)$$

$$Z = \sqrt{R^2 + X_C^2} \quad (5)$$

$$Z = \sqrt{R^2 + X^2} \quad (6) \text{ (General Form)}$$

$$I_Z = \sqrt{I_R^2 + I_L^2} \quad (7)$$

$$I_Z = \sqrt{I_R^2 + I_C^2} \quad (8)$$

$$I_Z = \sqrt{I_R^2 + I_X^2} \quad (9) \text{ (General Form)}$$

$$E_Z = \sqrt{E_R^2 + E_L^2} \quad (10)$$

$$E_Z = \sqrt{E_R^2 + E_C^2} \quad (11)$$

$$E_Z = \sqrt{E_R^2 + E_X^2} \quad (12) \text{ (General Form)}$$

PRACTICE EXERCISE SOLUTIONS

1. Voltage and current are in phase in an ac circuit containing only resistance.
2. If the vectors overlap one another, they are in phase.
3. (b) changing at its maximum rate. — The induced counter emf is directly proportional to the rate of change of current.
4. No — there is always some resistance in the connecting wires as well as in the inductor itself.
5. (b) passing through zero. — The rate of change is maximum when a sinusoidal waveshape passes through zero.
6. The phase relationship between voltage and current in a purely inductive circuit is 90° , with I lagging E.
7. In a circuit containing both inductance and resistance, the phase relationship between voltage and current will be between 0 and 90° , depending upon the values of L and R.
8. (a) voltage leads current.
9. $X_L = 2\pi fL$; or $X_L = \omega L$.
10. 628 ohms. — $X_L = 2\pi fL = 6.28 \times 1 \times 10^3 \times 1 \times 10^{-1} = 6.28 \times 10^2$, or 628 ohms.
11. 150 kHz. — $f = \frac{X_L}{2\pi L} = \frac{9.405 \times 10^3}{6.28 \times 1 \times 10^{-2}} = 1.5 \times 10^5$, or 150 kHz.
12. In a purely capacitive circuit, current leads voltage by 90° .
13. In a circuit containing capacitance and resistance, current leads voltage between 0 and 90° , depending on the values of C and R.
14. $X_C = \frac{1}{2\pi fC}$; or $X_C = \frac{1}{\omega C}$

PRACTICE EXERCISE SOLUTIONS (Continued)

15. 1.59K ohms. — $X_C = \frac{1}{2\pi fC} = \frac{1}{6.28 \times 1 \times 10^6 \times 1 \times 10^{-10}}$

$$= \frac{1}{6.28 \times 10^{-4}} = .159 \times 10^4$$

or 1.59K ohms.

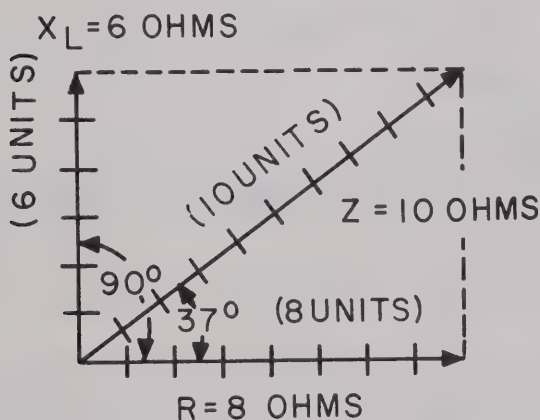
16. 15.9 kHz. — $f = \frac{1}{2\pi X_C C} = \frac{1}{6.28 \times 1 \times 10^3 \times 1 \times 10^{-8}}$

$$= \frac{1}{6.28 \times 10^{-5}} = .159 \times 10^5$$

$$= 15.9 \text{ kHz.}$$

17. (b) vector sum. — Since X_L and R are at different phase angles, they can only be added vectorially to determine the total opposition, or impedance.

18.



19. The vector representing resistance and circuit current is the reference vector in vector diagrams for series RL and RC circuits.

20. inductive; capacitive — An inductive circuit has a phase angle between 0 and 90° and a capacitive circuit has a phase angle between 270° and 360° .

PRACTICE EXERCISE SOLUTIONS (Continued)

$$21. Z = \sqrt{R^2 + X_C^2}$$

$$Z = \sqrt{R^2 + X_L^2}$$

$$\begin{aligned}
 22. \quad 316 \text{ ohms. — } Z &= \sqrt{100^2 + 300^2} = \sqrt{(1 \times 10^2)^2 + (3 \times 10^2)^2} \\
 &= \sqrt{1 \times 10^4 + 9 \times 10^4} = \sqrt{10 \times 10^4} \\
 &= 3.16 \times 10^2 \text{ or } 316 \text{ ohms.}
 \end{aligned}$$

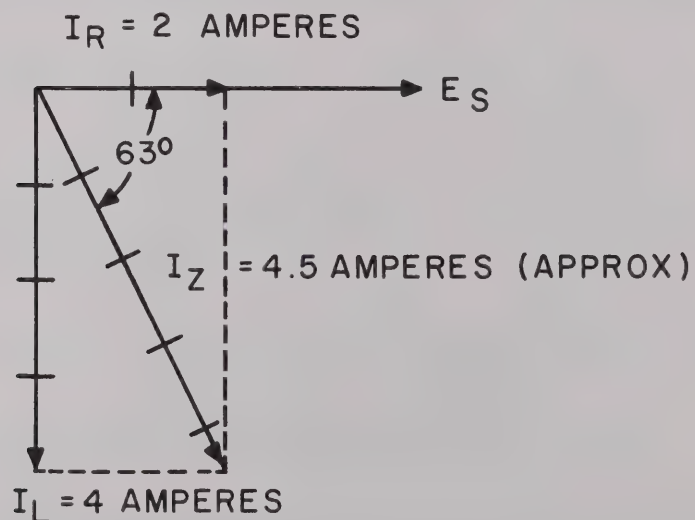
23. To determine the impedance in a parallel circuit, the individual branch currents are first computed. The total circuit current is then equal to the vector sum of the branch currents. The circuit impedance is then found by dividing the source voltage by the total circuit current.

24. To determine the total circuit impedance, the individual branch currents are computed as follows:

$$I_R = E/R = 100 \text{ volts}/50 \text{ ohms} = 2 \text{ amperes.}$$

$$I_L = E/X_L = 100 \text{ volts}/25 \text{ ohms} = 4 \text{ amperes.}$$

The total circuit current is found vectorially, as shown below in the accompanying diagram.



The total circuit is approximately 4.5 amperes from the vector diagram. The circuit impedance is, therefore:

$$\begin{aligned}
 Z &= E/I_T = 100 \text{ volts}/4.5 \text{ amperes} \\
 &= 22.2 \text{ ohms (approximately).}
 \end{aligned}$$

25. Yes — voltage always lags current in a capacitive circuit. The major difference occurs in vector diagrams, since voltage is used as the reference in parallel circuits and current is used as the reference in series circuits.

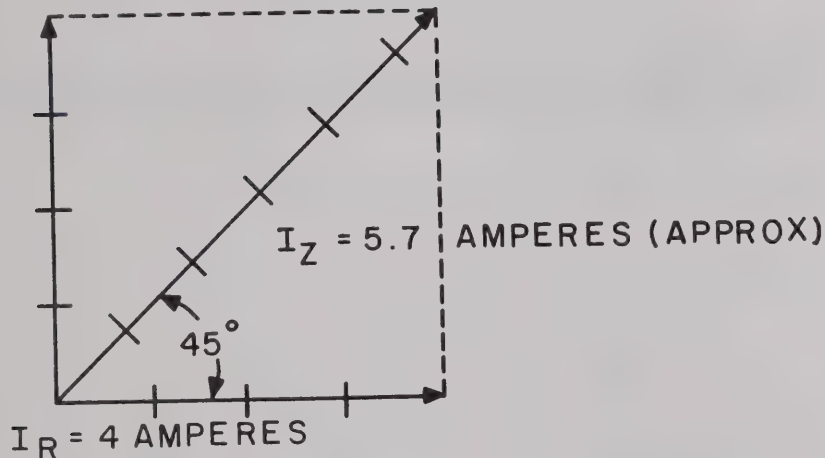
26. To determine the total circuit current, first determine the branch currents:

$$I_C = E/X_C = 100 \text{ volts}/25 \text{ ohms} = 4 \text{ amperes.}$$

$$I_R = E/R = 100 \text{ volts}/25 \text{ ohms} = 4 \text{ amperes.}$$

The total circuit current is found vectorially as shown in the following vector diagram.

$$I_C = 4 \text{ AMPERES}$$



27. The vector sum formula is used to determine the total circuit current. Circuit impedance is then determined by dividing the supply voltage by the circuit current.

$$28. I_R = 150 \text{ volts}/600 \text{ ohms} = .25 \text{ ampere.}$$

$$I_C = 150 \text{ volts}/300 \text{ ohms} = .5 \text{ ampere.}$$

$$\begin{aligned} I_T &= \sqrt{(2.5 \times 10^{-1})^2 + (5 \times 10^{-1})^2} \\ &= \sqrt{6.25 \times 10^{-2} + 25 \times 10^{-2}} \\ &= \sqrt{31.25 \times 10^{-2}} = 5.6 \times 10^{-1} \text{ (approximately), or .56 ampere.} \end{aligned}$$

$$Z = E/I_T = 150 \text{ volts}/.56 \text{ ampere}$$

$$= 268 \text{ ohms (approximately).}$$

PRACTICE EXERCISE SOLUTIONS (Continued)

29. The total voltage across the components is found by employing the vector sum formula. The circuit impedance is then equal to the total voltage divided by the circuit current.

$$30. E_L = I \times X_L = .05 \text{ ampere} \times 1000 \text{ ohms} = 50 \text{ volts.}$$

$$\begin{aligned} E_Z &= \sqrt{E_R^2 + E_L^2} = \sqrt{(10 \times 10^1)^2 + 5 \times 10^1)^2} \\ &= \sqrt{100 \times 10^2 + 25 \times 10^2} = \sqrt{125 \times 10^2} \\ &= \sqrt{1.25 \times 10^4} = 1.12 \times 10^2 \text{ or } 112 \text{ volts.} \end{aligned}$$

$$Z = E_Z / I = 112 \text{ volts} / .05 \text{ ampere} = 2.24 \text{ k}\Omega.$$

31. The impedance is found by measuring the supply voltage and circuit current. Impedance is then equal to the supply voltage divided by the circuit current ($Z = E/I$).

$$X_C = \frac{1000}{6.28 \times 10^3} = 0.0253$$

$$150^2 + 350^2 =$$

$$\begin{array}{r} 22500 \\ 122500 \\ \hline 145000 \end{array} + 122500$$

$$380$$

$$\begin{aligned} I_R &= 2.5 \\ I_L &= 2 \end{aligned}$$

$$\begin{array}{r} 301 \\ 100 \\ \hline 3.2 \end{array}$$

$$\frac{100}{40}$$

$$\frac{100}{50}$$

$$\sqrt{\frac{6.25}{10.25}}$$

$$\frac{200}{100}$$



1061A&B
EXAMINATION
CHECK SHEET

1061A&B

1. A - IN AN INDUCTIVE CIRCUIT, THE CURRENT -- LAGS THE VOLTAGE.
In a purely inductive circuit, current lags the voltage by 90° .
2. B - IN A CAPACITIVE CIRCUIT, THE VOLTAGE -- LAGS THE CURRENT.
In a purely capacitive circuit, voltage lags the current by 90° .
3. D - THE INDUCTIVE REACTANCE OF A 1.5 HENRY COIL AT A FREQUENCY OF 100 Hz IS -- 942 OHMS.
The inductive reactance is found by employing Equation 1 in the lesson.

$$X_L = 2\pi fL = 2 \times 3.14 \times 1 \times 10^2 \times 1.5 \\ = 6.28 \times 1.5 \times 10^2 = 9.42 \times 10^2 \text{ or } 942 \text{ ohms.}$$

4. C - WHAT IS THE REACTANCE OF A .1 μ F CAPACITOR AT A FREQUENCY OF 1 kHz? -- 1,590 OHMS.
The capacitive reactance is found by employing Equation 2 in the lesson.

$$X_C = \frac{1}{2\pi fC} = \frac{1}{6.28 \times 1 \times 10^3 \times .1 \times 10^{-6}} \\ = \frac{1}{.628 \times 10^{-3}} = 1.59 \times 10^3 \text{ or } 1,590 \text{ ohms.}$$

5. A - IN A VECTOR DIAGRAM FOR A PARALLEL RC CIRCUIT, WITH THE VOLTAGE VECTOR DRAWN HORIZONTALLY TO THE RIGHT, THE I_C VECTOR -- IS DRAWN UPWARD AT THE 90° PHASE.
Current leads voltage in a capacitive circuit. Therefore, the I_C vector must be drawn upward. (Vectors rotate counterclockwise)

6. A - IN A SERIES RL CIRCUIT, THE IMPEDANCE -- IS EQUAL TO THE VECTOR SUM OF R AND X_L .
The vector sum, which equals the impedance, can either be found graphically or with the vector sum formula.

7. A - WHAT IS THE IMPEDANCE OF A SERIES RC CIRCUIT IF $R = 150$ OHMS AND $X_C = 350$ OHMS?
-- 381 OHMS.

The impedance can be found by employing the vector sum formula:

$$Z = \sqrt{R^2 + X_C^2} = \sqrt{(1.5 \times 10^2)^2 + (3.5 \times 10^2)^2} \\ = \sqrt{2.25 \times 10^4 + 12.25 \times 10^4} = \sqrt{14.5 \times 10^4} \\ = 3.81 \times 10^2 \text{ or } 381 \text{ ohms.}$$

8. D - IN A PARALLEL RL CIRCUIT -- E IS THE REFERENCE VECTOR.
Since voltage is the same in all parts of a parallel circuit, it is used as the reference.

9. C - WHAT IS THE IMPEDANCE OF A PARALLEL RL CIRCUIT IF $R = 40$ OHMS, $X_L = 50$ OHMS AND $E = 100$ VOLTS -- 31.3 OHMS.

To determine the impedance, first find the branch currents.

$$I_R = E/R = 100 \text{ volts}/40 \text{ ohms} = 2.5 \text{ amperes}$$

$$I_L = E/R = 100 \text{ volts}/50 \text{ ohms} = 2 \text{ amperes}$$

Using the vector sum formula the total current is determined.

$$I_Z = \sqrt{I_R^2 + I_L^2} = \sqrt{2.5^2 + 2^2} \\ = \sqrt{6.25 + 4} = \sqrt{10.25} \\ = 3.2 \text{ amperes (approximately)}$$

The impedance is then found by dividing E by I_Z .

$$Z = E/I_Z = 100 \text{ volts}/3.2 \text{ amperes} = 31.3 \text{ ohms (approximately).}$$

GUIDE SHEETS FOR EXPERIMENTS 9506 SERIES

ALTERNATING CURRENT EFFECTS

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MATERIALS

THIS LIST INCLUDES ALL TOOLS, HARDWARE AND ELECTRONIC COMPONENTS NEEDED TO COMPLETE THE EXPERIMENTS IN THIS MANUAL.

- | | |
|---|--|
| 1 - Complete Design Console | 1 - 400 Ω Relay |
| 1 - Multimeter with Test Leads and
Spring Adapters | 1 - Transistor Socket with Leads |
| 1 - Soldering Iron | 1 - NPN Transistor |
| 1 - Pair Long-Nose Pliers | 1 - 9-Pin Tube Socket with Leads |
| 1 - Pair Wire Cutters | 1 - 12AU7 Tube |
| 1 - 470 Ω , 1/2 W, 20% Resistor | 1 - 1 M Ω Potentiometer with Bracket
and Leads |
| 1 - 1 k Ω , 1/2 W, 20% Resistor | 10 - Modular Connectors |
| 1 - 2.2 k Ω , 1/2 W, 5% Resistor | 2 - Tri-Mounts |
| 1 - 4.7 k Ω , 1/2 W, 20% Resistor | - No. 22 Solid Hookup Wire consisting
of 5" Black, 8" Red, 3" Yellow and
3" Blue |
| 2 - 10 k Ω , 1/2 W, 20% Resistors | - Rosin Core Solder Type 60/40,
Size .032 |
| 1 - 100 k Ω , 1/2 W, 20% Resistor | |
| 1 - 220 k Ω , 1/2 W, 20% Resistor | |
| 1 - .1 μ F Disk Capacitor | |
| 1 - 1000 μ F, 50V Electrolytic
Capacitor | |

INTRODUCTION

PARTS NEEDED

- 1 - Soldering Iron
- 1 - Pair Long-Nose Pliers
- 1 - Pair Wire Cutters
- 1 - 400 Ω Relay

- No. 22 Solid Hookup Wire
- Rosin Core Solder Type 60/40,
Size .032

OBJECTIVE

In the following procedure, you will wire connecting leads to the relay. The relay coil will be used as an inductor in some of the following experiments.

PROCEDURE

PREPARING THE RELAY

1. Figure 1 shows the connections to the 400 Ω relay. Your relay may appear slightly different but the connections are the same.
2. Referring to Figure 1, cut the proper color leads to the lengths indicated and remove 1/4" of insulation from one end of each wire. Remove 1/2" from the other end of each wire.
3. Connect the 1/4" ends of the leads to the lugs and solder each connection. (The lugs on your relay may not have connecting holes. If not, wrap the bare end of each piece of hookup wire around the end of its lug and solder it in place.)
4. The two red leads connect to the relay coil. Use only the red leads when using the relay coil as an INDUCTOR in the following experiments. Leave the other three leads unconnected.

NOTES

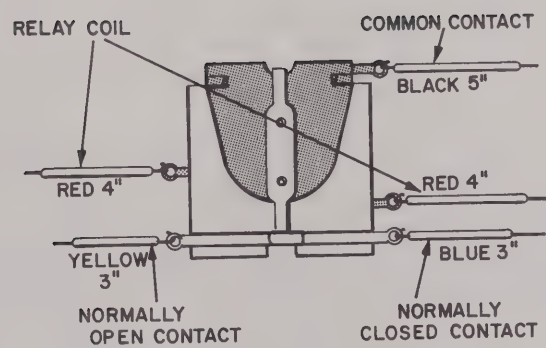


FIGURE I

NOTES

EXPERIMENT I

RC AND RL CIRCUITS

PARTS NEEDED

- | | |
|--|-------------------------------|
| 1 - Complete Design Console | 1 - .1 μ F Disk Capacitor |
| 1 - Multimeter with Test Leads and Spring Adapters | 1 - 400 Ω Relay |
| 1 - 2.2 k Ω , 1/2 W, 5% Resistor | 3 - Modular Connectors |
| 1 - 4.7 k Ω , 1/2 W, 20% Resistor | - No. 22 Solid Hookup Wire |

OBJECTIVE

Inductive and capacitive reactances are dependent upon the value of inductance and capacitance as well as upon the frequency. In this experiment you will investigate the action of series RC and RL circuits when the supply frequency is varied.

PART 1

PROCEDURE

SERIES RC CIRCUITS

1. Set up the circuit shown in Figure 1-1 on your design console. No layout is given since the circuit is quite simple. Be sure to use the sinewave output of the audio signal generator. The common terminal for the audio signal generator is the Regulated DC Negative Terminal.
2. The audio signal generator included in the design console has an approximate range of 300 Hz to 3 kHz. An arbitrary scale, 0 to 10, is used on the frequency dial (ADJUST FREQ.). These markings will be used in the following steps rather than actual frequencies. Remember, the frequency increases going from 0 to 10.
3. Turn on the design console. The ADJUST VOLTAGE control can be set fully counterclockwise since the low voltage supply is not used. Set the audio signal generator frequency control (ADJUST FREQ.) to 0. Using the output function on your multimeter, measure the voltages across R_1 and across C_1 in the circuit of Figure 1-1. Record the values in the first row of the chart of Figure 1-2.
4. Set the audio frequency to each of the settings indicated in the chart of Figure 1-2, and record the corresponding values of E_{C_1} and E_{R_1} . Because of the loading of the meter, there will be some error in the readings. However,

this will not affect the "TREND" of the results, which is the important factor.

Your results should show that, as the frequency increases, the voltage drop across the capacitor decreases and the voltage across the resistor increases. The reason for this is that capacitive reactance is inversely proportional to frequency.

5. Using the data in the chart of Figure 1-2, draw curves on the graph of Figure 1-3 showing how E_{C_1} and E_{R_1} vary with frequency. Although the chart and the graph contain the same information, the graph is much easier to interpret since it shows the circuit action at a glance. Your graph should have the general appearance of the one shown in Figure 1-4.

6. At one of the frequencies tested in the chart of Figure 1-2, the voltage across the capacitor will be approximately equal to the voltage across the resistor. At this frequency, the reactance of the capacitor is equal to the value of the resistor. Let's determine this frequency.

7. Record the ADJUST FREQ. control setting from the chart of Figure 1-2 at which E_{C_1} and E_{R_1} were nearly equal.

ADJUST FREQ. Control Setting 8

8. This setting can be converted into a frequency by rearranging the formula for X_C to solve for F :

$$X_C = \frac{1}{2\pi FC} = \frac{.159}{FC}$$

$$F = \frac{.159}{X_C C}$$

$$= \frac{.159}{2.2 \times 10^{-3} \times 10^{-7}} = \frac{1590}{2.2}$$

$$\frac{723}{1.0}$$

At this frequency, the value of X_C is the same as the value of R_1 . Remember, in a series circuit, voltage drops are equal when the impedances are equal.

9. Using the value of R_1 for X_C and using the value of C_1 for C , calculate the frequency and record it.

723 Hz

Frequency at Dial Setting = 723 Hz

Your calculation should have been about 700 Hz. If you wished to roughly calibrate the dial on the audio generator, you could substitute several different values for R_1 to produce equal values of E_{C_1} and E_{R_1} for each of the dial settings. A calibration chart could then be produced for the audio oscillator dial.

CONCLUSION

In a series RC circuit with a variable frequency applied, the voltage drops across the resistor and across the capacitor vary with the frequency. Since capacitive reactance is inversely proportional to frequency, the voltage across the capacitor decreases and that across the resistor increases as the frequency increases.

When dealing with series dc circuits, the sum of the individual voltage drops equals the applied source voltage. In a circuit containing reactance, this relationship does not hold due to the phase shift. The algebraic sum of the voltage drops in an RC circuit will be greater than the source voltage. However, when the voltages are added vectorally, they will equal the source voltage.

Note: Because of the meter loading, some of your measurements may not show that the algebraic sum of E_{C_1} and E_{R_1} is greater than the source. Every meter introduces an error which modifies the theoretical results.

PART 2

PROCEDURE

SERIES RL CIRCUITS

1. Set up the circuit shown in Figure 1-5. Again, use the sinewave output of the audio generator. The relay coil will be used as the inductor for this experiment.
2. To investigate the action in an RL circuit, turn on the design console and set the audio generator ADJUST FREQ. control to the frequencies listed in the chart of Figure 1-6. Record the corresponding values of E_{R_1} and E_{L_1} in the chart of Figure 1-6.
3. Using the values in the chart of Figure 1-6, plot curves of E_{R_1} and E_{L_1} on the graph of Figure 1-7. Your curves should look similar to the ones shown in Figure 1-8.

CONCLUSION

In a series RL circuit, the voltage drop across the inductor increases with frequency; and the voltage across the resistor decreases. This occurs since inductive reactance is directly proportional to frequency.

As in the series RC circuit, the algebraic sum of the voltage drops across the resistor and inductor does not equal the source voltage. Whenever reactance is included in an ac circuit, the voltage drops must be added vectorally.

NOTES

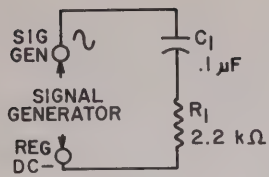


FIGURE 1-1

FREQ.	E_{R1}	E_{C1}
0	1.0	3.4
1	1.0	3.3
2	1.0	3.3
3	1.0	3.3
4	1.1	3.3
5	1.2	3.2
6	1.3	3.1
7	1.6	2.9
8	1.8	2.0
9	0	0
10	0	0

FIGURE 1-2

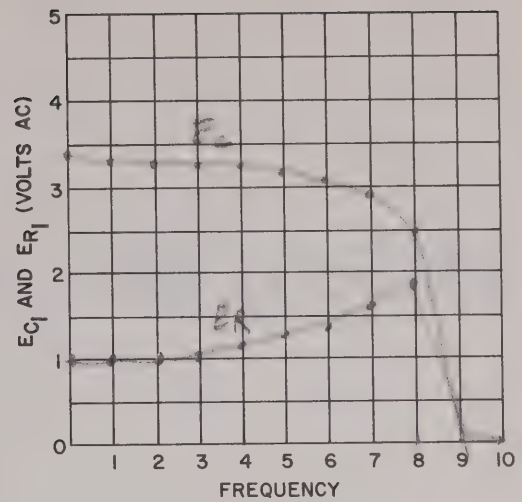


FIGURE 1-3

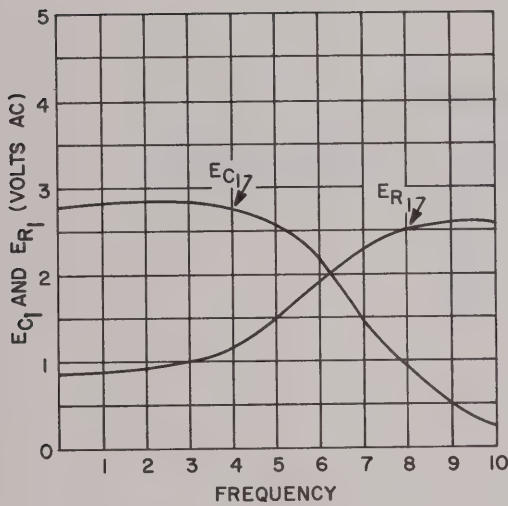


FIGURE 1-4

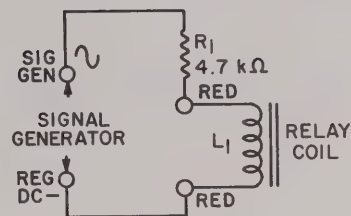


FIGURE 1-5

FREQ.	E_{R1}	E_{L1}
0	3.0	2.3
1	3.0	2.3
2	3.0	2.3
3	3.0	2.4
4	3.0	2.5
5	2.9	2.6
6	2.9	2.8
7	2.7	3.0
8	2.0	3.0
9	0	0
10	0	0

FIGURE 1-6

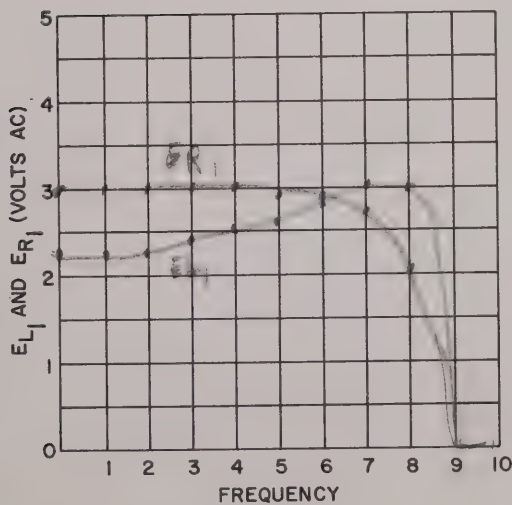


FIGURE 1-7

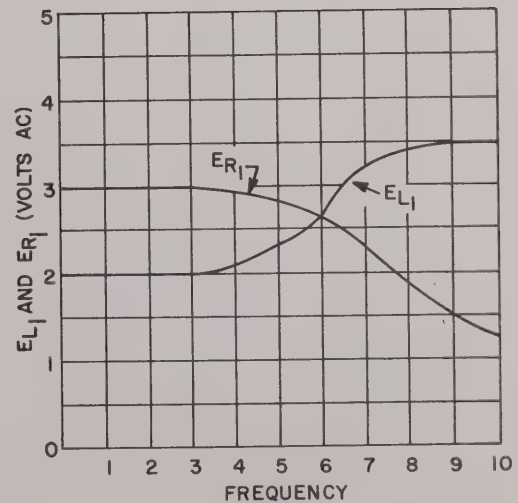


FIGURE 1-8

NOTES

THIRD CLASS MAIL ENCLOSURE

QUESTION SHEETS FOR LABORATORY
SHIPMENTS ELI-4, ELI-5, ELI-6

ELQ-2

$$X_C = \frac{6.28 \times 10^3 \times 5 \times 10^{-6}}{1} = 314$$

$$X_C = \frac{1}{2\pi f C}$$

$$f = \frac{1}{2\pi X_C C}$$

$$f = \frac{1}{2\pi \times 314 \times 5 \times 10^{-6}} = 1000$$

$$f = \frac{1}{2\pi \times 314 \times 5 \times 10^{-6}} = 1000$$

$$f = 1000 \text{ Hz} = 1 \text{ kHz}$$



ONE OF THE

BELL & HOWELL SCHOOLS

9506-1A
EXAMINATION
CHECK SHEET

1. D - WHAT IS THE X_C OF A .5 μ F CAPACITOR AT A FREQUENCY OF 1 kHz? -- 318 Ω .
The X_C is calculated as follows:

$$X_C = \frac{.159}{fC} = \frac{.159}{1 \times 10^3 \times .5 \times 10^{-6}} = .318 \times 10^3 = 318\Omega.$$

2. A - IN A SERIES RC CIRCUIT -- AS FREQUENCY DECREASES, E_R DECREASES.
In a series RC circuit the voltage drop across the resistor increases and that across the capacitor decreases as frequency increases. Remember, X_C is inversely proportional to frequency.

3. A - A SERIES RC CIRCUIT HAS THE FOLLOWING VALUES: $R = 1.5 \text{ k}\Omega$ AND $C = .1 \mu\text{F}$. AT WHAT FREQUENCY WILL THE VALUE OF X_C EQUAL R ? -- 1 kHz.

To solve for the frequency, the formula for capacitive reactance is rearranged:

$$X_C = \frac{.159}{fC}$$

$$f = \frac{.159}{CX_C} = \frac{.159}{.1 \times 10^{-6} \times 1.5 \times 10^3} = \frac{.159}{.15 \times 10^{-3}} = 1.06 \times 10^3 \text{ or } 1 \text{ kHz (approx.)}.$$

4. D - IN A SERIES RL CIRCUIT, -- AS FREQUENCY INCREASES, E_L INCREASES.
In a series RL circuit the voltage drop across the resistor decreases and that across the inductor increases as frequency increases. Remember, X_L is directly proportional to frequency.

5. C - WHAT IS THE INDUCTIVE REACTANCE OF A 500 mH INDUCTOR AT A FREQUENCY OF 5 kHz?
-- 16 k Ω .

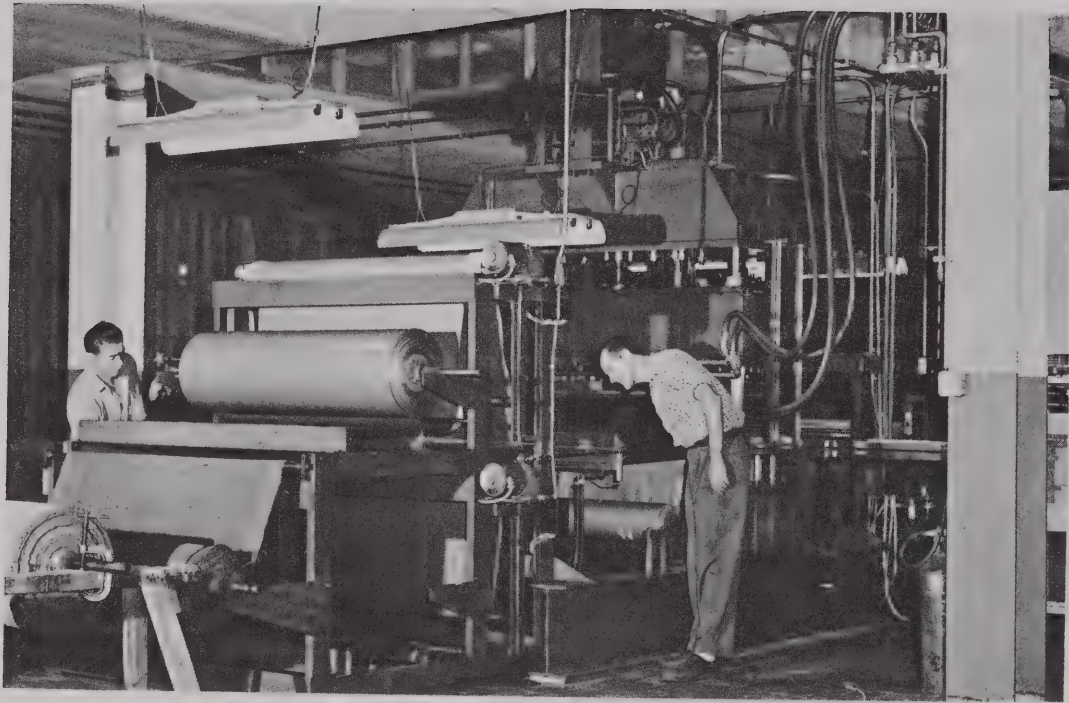
The inductive reactance is calculated as follows:

$$X_L = 2\pi fL = 6.28 \times 5 \times 10^3 \times .5 = 6.28 \times 2.5 \times 10^3 = 16 \text{ k}\Omega \text{ (approx.)}.$$

FREQUENCY EFFECTS ON RLC CIRCUITS

1064





A resonant LC circuit is used to control the frequency of the generated r-f in this high-frequency heating unit used to quilt plastics.

Courtesy Thermatron Corp.

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True progress never commands the human race to start from scratch. Civilization is an accumulation of living values, an organic thing. Without change, there can be no growth; but without tradition there can be no civilization.

—Dorothy Thompson

FREQUENCY EFFECTS ON RLC CIRCUITS

One of the most important characteristics of any radio or TV receiver is its ability to select the desired signal from among the many signals that are being simultaneously transmitted by the various stations in a particular area. Using the Standard Broadcast Band (535-1605 kHz) as an example, imagine the garbled conglomeration of sounds that would be produced by your radio speaker if all stations were received at the same time.

Even though all of the stations in the Standard Broadcast Band transmit signals that are basically the same, the signal from each station has a characteristic that distinguishes it from the other signals — the frequency of the carrier signal is different. In Chicago, for example, the carrier frequency of WGN is 720 kHz, that of WBBM is 780 kHz and that of WLS is 890 kHz.

When you “tune” in a particular station, let’s say WGN, you are actually adjusting some electrical components in your radio to select a carrier signal that has a frequency of 720 kHz and to reject all other carrier frequencies. How does this occur? The purpose of this lesson is to explain the basic electronic principles that account for the ability of circuits to “tune in” the signal from the desired station.

EFFECT OF FREQUENCY ON INDUCTIVE REACTANCE

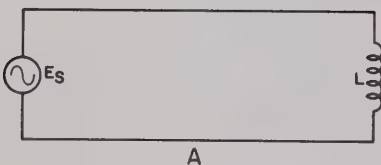


Figure
1

When an inductor is connected into a simple ac circuit, as in Figure 1A, it offers opposition to current. The opposition is called inductive reactance (X_L) and is proportional to the inductance (L) of the inductor and the frequency (f) of the voltage source. As discussed in a previous lesson, the relationship of these quantities is:

$$X_L = 2\pi fL.$$

This equation tells us that X_L (inductive reactance) is directly proportional to both f (frequency) and L (inductance). That is, an increase in either f or L causes a proportional increase in X_L ; a decrease in either f or L causes a proportional decrease in X_L .

When the inductor of Figure 1A is constructed with a fixed value of inductance, the only variable that affects inductive reactance is the frequency

of the voltage source. Thus, in Figure 1A, THE INDUCTIVE REACTANCE VARIES DIRECTLY WITH FREQUENCY.

This relationship is shown in the graph of Figure 1B, where f is plotted on the horizontal axis and X_L is plotted on the vertical axis. It is customary to plot graphs with the independent variable (the one that you actually change) on the horizontal axis and the dependent variable (the resulting change) on the vertical axis. Therefore, the graph of Figure 1B tells us that, as you increase the frequency of the voltage source, the inductive reactance increases linearly in direct proportion.

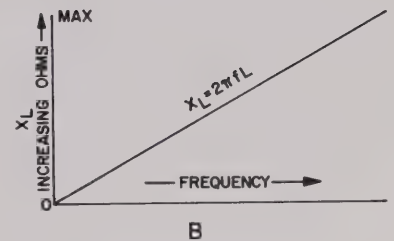


Figure 1

EFFECT OF FREQUENCY ON CAPACITIVE REACTANCE

When a capacitor is connected into a simple ac circuit, as in Figure 2A, it also offers opposition to current which is called capacitive reactance (X_C) and is proportional to the capacitance (C) of the capacitor and the frequency (f) of the voltage source. The relationship of these quantities is:

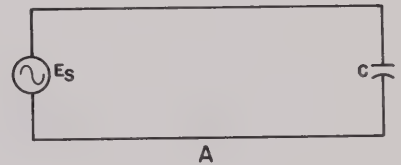


Figure 2

$$X_C = \frac{1}{2\pi fC}$$

Whenever an equation is in this form (the quantities on the right side are under the number "1"), it tells us that the quantity on the left side is inversely proportional to the quantities on the right side. That is, an increase in either f or C causes a proportional decrease in X_C ; a decrease in either f or C causes a proportional increase in X_C .

When the capacitor of Figure 2A is constructed with a fixed value of capacitance, the only variable that affects capacitance reactance is the frequency of the voltage source. Thus, in Figure 2A, THE CAPACITIVE REACTANCE VARIES INVERSELY WITH FREQUENCY.

Drawn on the same general plan as Figure 1B, the graph for capacitive reactance is shown in Figure 2B. Notice that the plot for X_C is a curve, rather than a straight line. This tells us that, as you increase the frequency of the voltage source, the capacitive reactance decreases at a nonlinear rate. At this time, however, we are not concerned about the shape of the X_C curve; but we are concerned about the fact that changes in frequency affect capacitive reactance opposite to inductive reactance.

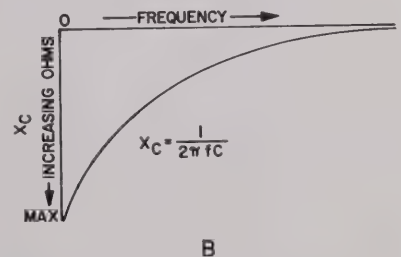


Figure 2

EFFECT OF FREQUENCY ON RESISTANCE

The expressions for inductive reactance, $X_L = 2\pi fL$, and capacitive reactance, $X_C = \frac{1}{2\pi fC}$ both contain an "f." Any change of frequency changes the reactance of the component, as shown in Figures 1 and 2. So far, nothing has been said about the effect of frequency on resistance. In the Ohm's Law relationship, $R = E/I$, no "f" is involved. For all practical purposes, a change of frequency does not affect the resistance of the circuit. If, in a purely resistive circuit, an ac voltage source E at a frequency of 60 Hz provides a current of 50 milliamperes, then the current in the same resistive circuit is still 50 milliamperes when the frequency of the voltage source is changed to 1000 Hz.

RESULTANT REACTANCE

In a previous lesson we found that the circuit current has a specific phase relationship to the circuit voltage when a reactive component (L or C) is connected across an ac voltage source. Referring to the inductive circuit of Figure 1A, the current-voltage phase relationship is shown by the vector diagram of Figure 3A and indicates that the voltage, E_s , leads the current, I_L , by 90° . In the capacitive circuit of Figure 2A, the current-voltage phase relationship is shown in Figure 3B and indicates that the voltage, E_s , lags the current, I_C , by 90° .

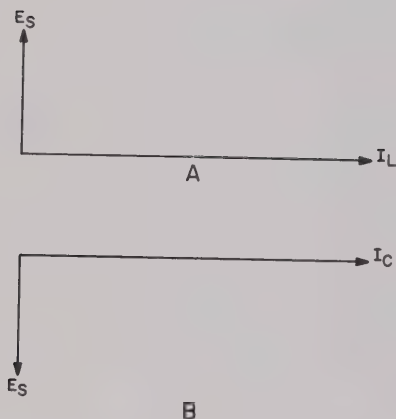
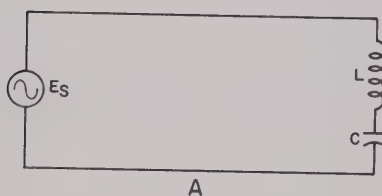


Figure 3



When an inductor and a capacitor are series connected, as in Figure 4A, the current-voltage phase relationships are as shown in Figure 4B. Since there is only one current in a series circuit and it is the same for all components, the circuit current is labelled I_T . The voltage across each of the reactive components maintains the same phase relationship to the current as it had in the previous circuits. Thus, E_L is shown leading the current while E_C is shown lagging the current.

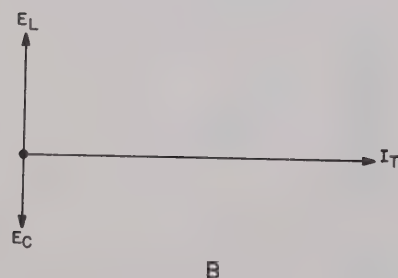


Figure 4

Notice, in Figure 4B, that E_L and E_C are 180° out-of-phase and oppose each other. Since the current is the same through both components, the opposing voltages can only be due to the fact that the reactances oppose each other. Therefore, in a series ac circuit, the effective, or RESULTANT REACTANCE, is the difference between the individual reactances. As an equation, the resultant reactance is:

$$X = (X_L - X_C).$$

Suppose an ac circuit like that of Figure 4A contains an X_L of 200 ohms and an X_C of 150 ohms. The resultant reactance is:

$$X = (X_L - X_C)$$

$$= 200 - 150$$

$$= 50 \text{ ohms.}$$

In some cases, the X_C may be larger than the X_L . If $X_L = 1000$ ohms and $X_C = 5000$ ohms, the difference is:

$$X = (X_C - X_L)$$

$$= 5000 - 1000$$

$$= 4000 \text{ ohms.}$$

Following the rules of arithmetic, to find a difference, the smaller is subtracted from the larger. In the above examples, X_L and X_C may be treated as vectors which are 180° out-of-phase.

RESONANCE

The combined effect of inductive and capacitive reactance in a series RLC circuit is shown in Figure 5, which combines the curves of Figures 1A and 2A into a single graph. The horizontal frequency line is used as a common reference or base, with X_L customarily plotted in a positive or upward direction and X_C plotted in a negative or downward direction. Acting in opposition, the effects of inductive and capacitive reactance tend to neutralize each other. This combined effect is indicated by the dashed line "effective reactance" curve, X_s , drawn between the X_L and X_C curves.

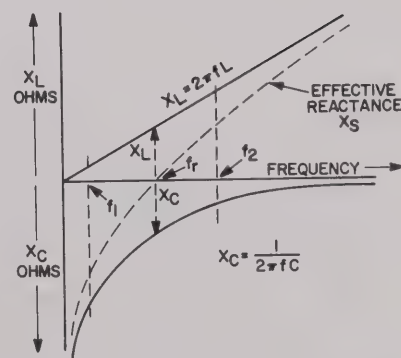


Figure 5

Notice that the X_s curve crosses the horizontal line at the point labeled f_r . At this point, the value of X_L (upwards) equals the value of X_C (downwards), and a condition called **RESONANCE** exists. When the frequency of the source voltage causes these conditions, the circuit is said to be **RESONANT** and is operating at its **RESONANT FREQUENCY**, f_r , as indicated on the base line of Figure 5.

FREQUENCY EFFECTS ON RLC CIRCUITS

AT FREQUENCIES BELOW THE RESONANT FREQUENCY, f_r , such as f_1 , X_C is greater than X_L , and the resultant reactance is capacitive, and THE CIRCUIT IS SAID TO BE CAPACITIVE. For any frequency above f_r , such as f_2 , opposite conditions exist, X_L is greater than X_C , and THE CIRCUIT IS SAID TO BE INDUCTIVE. However, at resonance, X_L is equal to X_C , the effective reactance is zero, and the circuit acts purely resistive, as determined by the actual resistance it contains.

To take advantage of circuit conditions at resonance, it is necessary to calculate the resonant frequency, f_r . At resonance, $X_L = X_C$ and therefore:

$$\left(2\pi f_r L = \frac{1}{2\pi f_r C} \right)$$

When this equation is rearranged as shown in Appendix A, it becomes the resonant frequency equation:

$$\left(f_r = \frac{1}{2\pi \sqrt{LC}} \right) \quad (1)$$

where: f_r = resonant frequency in hertz,

L = inductance in henries,

C = capacitance in farads, and

$\pi = 3.14$.

The formula for resonant frequency may be simplified somewhat by dividing 2π into 1, producing the following formula:

$$f_r = \frac{.159}{\sqrt{LC}} \quad (2)$$

This formula is accurate enough for most calculations and will be used in this lesson.

RESONANT FREQUENCY CALCULATIONS

As an example of the use of Equation 2, assume that, in a series LC circuit, "L" is 80 microhenries (80×10^{-6} henries) and "C" is 316 picofarads (316×10^{-12} farads). Substituting these values in the resonant frequency equation:

$$\begin{aligned} f_r &= \frac{.159}{\sqrt{LC}} = \frac{.159}{\sqrt{80 \times 10^{-6} \times 316 \times 10^{-12}}} \\ &= \frac{.159}{\sqrt{8.0 \times 10^{-5} \times 3.16 \times 10^{-10}}} \\ &= \frac{.159}{\sqrt{25.28 \times 10^{-15}}} = \frac{.159}{\sqrt{2.528 \times 10^{-14}}} \\ &= \frac{.159}{1.59 \times 10^{-7}} = .1 \times 10^7 \\ &= 1.0 \times 10^6 \text{ Hz or } 1 \text{ MHz.} \end{aligned}$$

SERIES RLC CIRCUIT ACTION

In the series circuit shown in Figure 6, a resistor, an inductor and a capacitor are connected in series across a constant voltage, variable frequency source whose center frequency is 1000 kHz (1 MHz) and which is variable 60 kHz above and below its center frequency. Since the LC components of Figure 6 are resonant at 1000 kHz, the circuit is called a SERIES RESONANT CIRCUIT. By varying the source frequency and measuring the resultant changes in current, we can determine some important characteristics of the circuit. When plotted, the ammeter measurements provide the "I" curve shown in Figure 7. The "I" curve indicates that the current is minimum at the lowest frequency. As the source frequency is increased, the circuit current is increased until it reaches a maximum at 1000 kHz. As the source frequency is increased further, the current decreases at approximately the same rate as it increased.

Consider the Ohm's Law relationship between voltage, current and resistance; with a constant voltage ac source, the change of frequency causes a change of impedance, which allows variation of the current. As explained for the

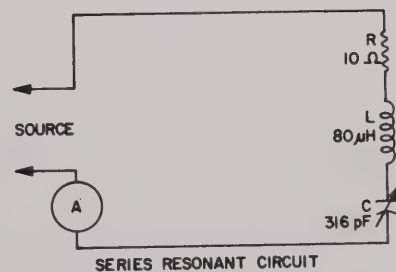


Figure 6

FREQUENCY EFFECTS ON RLC CIRCUITS

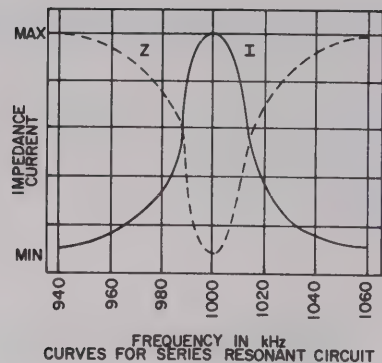
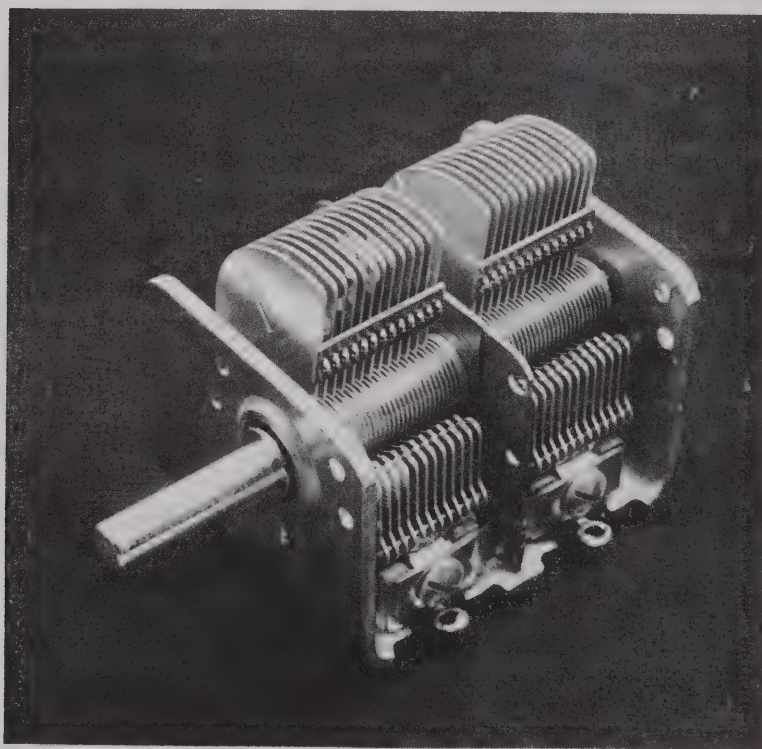


Figure 7

effective reactance curve of Figure 5, the dashed line "Z" curve of Figure 7 indicates the change of circuit impedance as the source frequency is changed. With minimum impedance at 1000 kHz, the effective reactance must be zero, and only the resistor offers opposition to the current (current is maximum at this frequency).



Double-gang variable capacitors are used in radio receivers to simultaneously vary the frequency of two resonant circuits.

DeVry Photo

The following Practice Exercise questions cover the subjects which you have just studied. They are:

EFFECT OF FREQUENCY ON INDUCTIVE REACTANCE

EFFECT OF FREQUENCY ON CAPACITIVE REACTANCE

EFFECT OF FREQUENCY ON RESISTANCE

RESULTANT REACTANCE

RESONANCE

RESONANT FREQUENCY CALCULATIONS

1. Inductive reactance varies (a) directly with frequency, (b) inversely with frequency.
2. Assume that an inductor has a reactance of 1000 ohms at a particular frequency. What is the value of inductive reactance if the frequency is halved?
3. How does the phase relation between voltage and current in a capacitive circuit differ from that in an inductive circuit?
4. Capacitive reactance varies (a) directly with frequency, (b) inversely with frequency.
5. Is resistance normally affected by frequency?
6. How is the resultant reactance determined in a series LC circuit?
7. Assume $X_L = 1500$ ohms and $X_C = 2500$ ohms in a series LC circuit. What is the resultant, or total reactance, and is the circuit inductive or capacitive?
8. What is the relation between X_L and X_C in a series RLC circuit at resonance?

9. In a series RLC circuit, at frequencies below the resonant frequency, is the circuit inductive, resistive or capacitive?
10. At what frequency is a series RLC circuit resistive?
11. What is the formula for determining the resonant frequency of a series RLC circuit?
12. What is the resonant frequency of a series RLC circuit if $C = 100 \text{ pF}$ and $L = 100 \text{ } \mu\text{H}$?

$$X_L = 2\pi f L = 6.28 \times 10^6 \times 8 \times 10^{-5}$$

$$= 502$$

$$50.$$

$$X_C = \frac{1}{2\pi f C} = \frac{1}{6.28 \times 10^6 \times 3.16 \times 10^{-10}}$$

$$\frac{10000}{20}$$

$$X_C - X_L = 502$$

$$Z = \frac{E}{I}$$

$$\begin{array}{r} 3.16 \\ 6.3 \\ \hline 9.48 \\ 1896 \\ \hline 19908 \end{array}$$

$$E = I_C X_C$$

$$I = I_C + I_L$$

To summarize conditions found in a series resonant circuit: THE CURRENT IS MAXIMUM, THE EFFECTIVE REACTANCE IS ZERO, AND THE IMPEDANCE IS MINIMUM AND EQUAL TO THE CIRCUIT RESISTANCE.

Resistance is a very important factor in a series resonant circuit like Figure 6. Although resistance does not affect the resonant frequency, it does affect all other characteristics of the circuit. For example, if the source voltage of Figure 6 is 10 millivolts, the circuit current at resonance is 1 milliampere. Since X_L and X_C are each about 500 ohms, the voltage across each of the reactive components is 500 millivolts. An explanation of this condition is given later in this lesson. Increasing the resistance from 10 ohms to 20 ohms decreases the circuit current to .5 milliampere and decreases the voltage across each reactive component to 250 millivolts. Additional effects of resistance in a resonant circuit are also discussed later in the lesson.

PARALLEL RLC CIRCUIT

Figure 8 shows a parallel RLC circuit that has the same component values as in Figure 6 so that the circuit is a **PARALLEL RESONANT CIRCUIT** at a frequency of 1000 kHz. The "R" is not a separate resistor; it represents the resistance of the wire forming the coil of the inductor.

Although X_L and X_C of Figure 8 vary with frequency in the same manner as in Figure 6, the parallel RLC connection causes exactly opposite effects.

For the series RLC circuit shown in Figure 6, the inductive and capacitive reactances vary with frequency. The parallel RLC connection causes entirely different actions. Starting with dc or zero frequency, there will be no current in the capacitive branch and maximum current in the inductive branch, although the full voltage is across both branches.

As the source frequency is increased, the inductive reactance increases, causing a reduction of current in the LR branch, while the capacitive reactance decreases, causing an increase of current in capacitor C. Momentarily disregarding the resistance in the inductive branch, the inductive reactance causes the current to lag the source voltage by 90° , while the capacitive reactance causes the current to lead the voltage by 90° . The relationship of the branch currents to the source voltage is shown in Figure 9. Notice that the two reactance currents are 180° out-of-phase with each other so that, with negligible resistance in the circuit, the current supplied by the source equals the difference between the leading and lagging reactive currents.

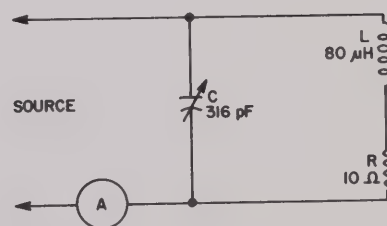


Figure 8

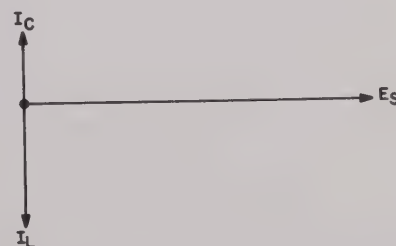


Figure 9

FREQUENCY EFFECTS ON RLC CIRCUITS

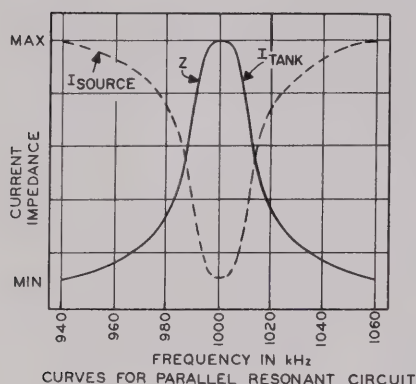


Figure 10

The parallel resonant circuit of Figure 8 has the characteristics shown by the curves of Figure 10. As indicated by the dashed line curve, the frequencies below 940 kHz cause the SOURCE CURRENT TO BE MAXIMUM. As the frequency is increased, the inductive reactance increases, causing a reduction of current in the inductive branch. Simultaneously, the capacitive reactance decreases, causing an increase of current in the capacitive branch.

These changes of reactance cause the difference between the inductive and capacitive currents to decrease so that the source current is decreased. This action continues until, at resonance (1000 kHz), the inductive and capacitive reactances are equal. Under these conditions, the source provides current only to compensate for the losses or dissipation in the resistance; therefore, at resonance the source current is minimum.

Although source current is minimum at resonance, the parallel resonant circuit current (I_{tank} of Figure 10) reaches its maximum value at resonance. This circuit is often called a "tank circuit" because, at resonance, it retains the circulating branch circuit current similar to a storage tank. The branch current circulation is comparable to the movement of a pendulum. For example, neglect the LR branch resistance of Figure 8 and assume that the source polarity causes the branch current electrons to build up on the upper capacitor plate. (The pendulum is at one end of its swing.) On the next source alteration, the capacitor discharges through the coil, which develops an expanding magnetic field as the electrons flow toward the lower capacitor plate. (The pendulum is now descending.) As the charge on the upper plate decreases, the magnetic field of the inductor increases, until the capacitor and inductor voltages are equal. (Pendulum travel reaches its midpoint.) Attaining its maximum value, the magnetic field begins to collapse; however, the electrons continue building a charge on the lower capacitor plate. (The pendulum is now ascending.) When the magnetic field diminishes to zero, there is no further electron flow and the charge on the lower capacitor plate is maximum. (The pendulum reaches the other end of its swing.) The circulating action of the current in the tank circuit then reverses, as does the source alternation, and begins building a charge on the upper capacitor plate again. The actions of the circuit elements are essentially the same, only the direction of electron flow is reversed.

The nature of a parallel RLC circuit at any frequency other than the resonant frequency is determined by the branch carrying the most current. At frequencies below resonance, the inductive reactance is less than the capacitive reactance, the current in the inductive branch is greater, and the circuit is inductive. At frequencies above resonance, the capacitive reactance is less than the inductive reactance, the current in the capacitive branch is greater, and the circuit is capacitive.

The total impedance of a circuit is determined by the Ohm's Law relationship of the voltage across the impedance and the current through it. Still assuming a constant voltage source, the curves of Figure 10 show minimum source current at resonance. Since maximum impedance must exist to reduce the source current to minimum, the Z curve of Figure 10 indicates maximum impedance at resonance. At frequencies above and below resonance, the impedance of a parallel circuit decreases.

For a parallel circuit, resonance can be defined in two ways:

- ① the frequency at which the line or supply current is minimum; and
- ② the frequency at which the inductive reactance, X_L , is equal to the capacitive reactance, X_C .

Practical circuits contain some resistance in the inductive branch that causes the two previous conditions to occur at slightly different frequencies. However, the difference between the two resonant frequencies is so small that, for most purposes, the resonant frequency of parallel circuits can be found by using the equation for series circuits:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \text{ or } \frac{.159}{\sqrt{LC}}$$

To summarize the most important conditions in a parallel circuit at resonance: THE IMPEDANCE IS MAXIMUM, THE SUPPLY CURRENT IS AT A MINIMUM AND DEPENDS ON THE RESONANT CIRCUIT RESISTANCE.

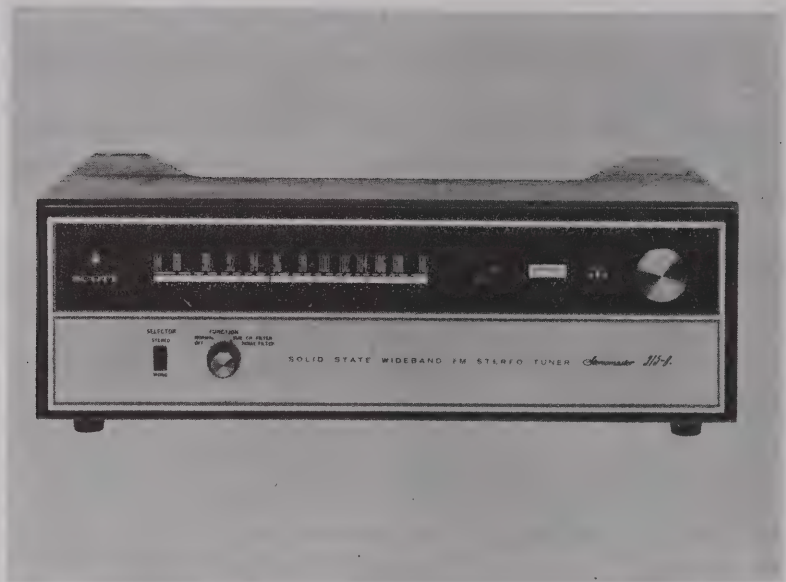
THE FIGURE OF MERIT (Q)

In a circuit containing only inductors and capacitors, there is always some unavoidable resistance in the wires of coils, capacitors and connections. To obtain best results in resonant circuits, it is desirable to keep the resistance as low as possible. Although it is impossible to make an inductor with wire which has no resistance, a large wire size can be used to keep the resistance low.

In a series circuit consisting of an inductor and a resistor, if the resistance is kept low, the power dissipated as heat will also be low. For resonant circuits, the power loss should be extremely low; therefore, a coil with low resistance is considered a better inductor than one with a high resistance.

The resistance of an inductor determines its quality, and the letter "Q," used to designate what is called the **FIGURE OF MERIT** of a coil, represents the ratio of the reactance to the resistance. Expressed as an equation:

$$Q = \frac{X_L}{R} = \frac{2\pi fL}{R} = \frac{\omega L}{R} \quad (3)$$



Circuit bandwidth is important in a stereo FM tuner. The bandwidth must be wide enough to pass all of the signal but not be wide enough to pass undesired adjacent signals.

Courtesy H. H. Scott

This equation indicates that the Q varies inversely with R . Q is higher when the resistance is lower and is lower when the resistance is higher. Thus, if R in Figure 6 or 8 is 20 ohms, inductor L is 80 microhenries, and the source has a frequency of 1000 kHz, the Q is:

$$\begin{aligned} X_L &= 2\pi fL \\ &= 6.28 \times 1 \times 10^6 \times 8.0 \times 10^{-5} \\ &= 500 \text{ ohms (approx.)} \end{aligned}$$

$$Q = \frac{X_L}{R} = \frac{500}{20} \text{ or } 25.$$

The Q represents no unit of measurement, but is merely a number expressing a ratio.

If inductor L is rewound with larger wire so that its resistance is only 10 ohms, the figure of merit becomes:

$$Q = \frac{X_L}{R} = \frac{500}{10} \text{ or } 50.$$

With the same inductance and half the resistance, the Q is twice as large.

In a series resonant circuit like that of Figure 6, one use of Q is to determine the voltage across each of the reactive components. At resonance, the voltage across each reactive component is equal to the source voltage multiplied by Q . Therefore, in Figure 6, when the source voltage is 10 millivolts and Q is 50, E_{X_C} and E_{X_L} are each 500 millivolts. When Q is only 25, each voltage is 250 millivolts.

The Q factor can be used to derive the approximate impedance of parallel resonant circuits by means of the following equations:

$$Z_P = QX_L, \text{ or} \quad (4)$$

$$Z_P = QX_C. \quad (5)$$

These equations can only be used when the resistor is in series with one of the reactance elements, as shown in Figure 8.

As an example of the use of the impedance equations containing Q , we will again assume the values for the elements shown in Figure 8: R equals 20 ohms and X_L equals 500 ohms. As previously determined, the figure of merit for these values is a Q of 25. The impedance will be:

$$Z = QX_L = 25 \times 500 = 12,500 \text{ ohms.}$$

EFFECT OF RESISTANCE ON RESONANCE CURVE

Coil resistance in a series resonant circuit reduces the maximum current, while in a parallel resonant circuit, it decreases the impedance. Since maximum current is desired in most series circuits and maximum impedance in parallel circuits, an increase of coil resistance is undesirable in both series and parallel resonant circuits.

When the coil resistance is increased, the Q of the circuit decreases. This causes the resonance curve to be flattened somewhat, as shown in Figure 11, so that the circuit is responsive to a wider band of frequencies. A tuned circuit with a low Q does not select as sharply as a circuit with a high Q .

Handwritten notes and diagrams:

- $Z = X_L / Q$
- $Z = \frac{X_L^2}{R}$
- ~~$Z = \frac{X_L}{R}$~~

Handwritten notes and diagrams:

- $Q = \frac{X_L}{R}$
- $Z_P = \frac{X_L^2}{R}$
- $I = \frac{E}{R}$
- Diagram of a series circuit with a resistor R and an inductor X_L in series, connected to a voltage source E .

Thus, Q is a measure of the ability of a tuned circuit to select or reject a band of frequencies.

BANDWIDTH — BANDPASS

For resonant circuits, the bandwidth of a circuit is defined as a range of frequencies which provides approximately the same current, or "response," as the resonant frequency. Very often, the width of this band is called the **BANDPASS** of the circuit. In practice, the limits of the bandpass are taken to be points on the resonance curve corresponding to approximately .707 of the maximum response (current for a series circuit or impedance for a parallel circuit). In Figure 11, the maximum response occurs at a resonant frequency of 1000 kHz, and the vertical dashed lines, on both sides of resonance, indicate the approximate points of .707 of the maximum. The bandpass of the curve having the lowest R and the highest Q is from approximately 990 kHz to 1010 kHz, providing a total bandpass of about 20 kHz.

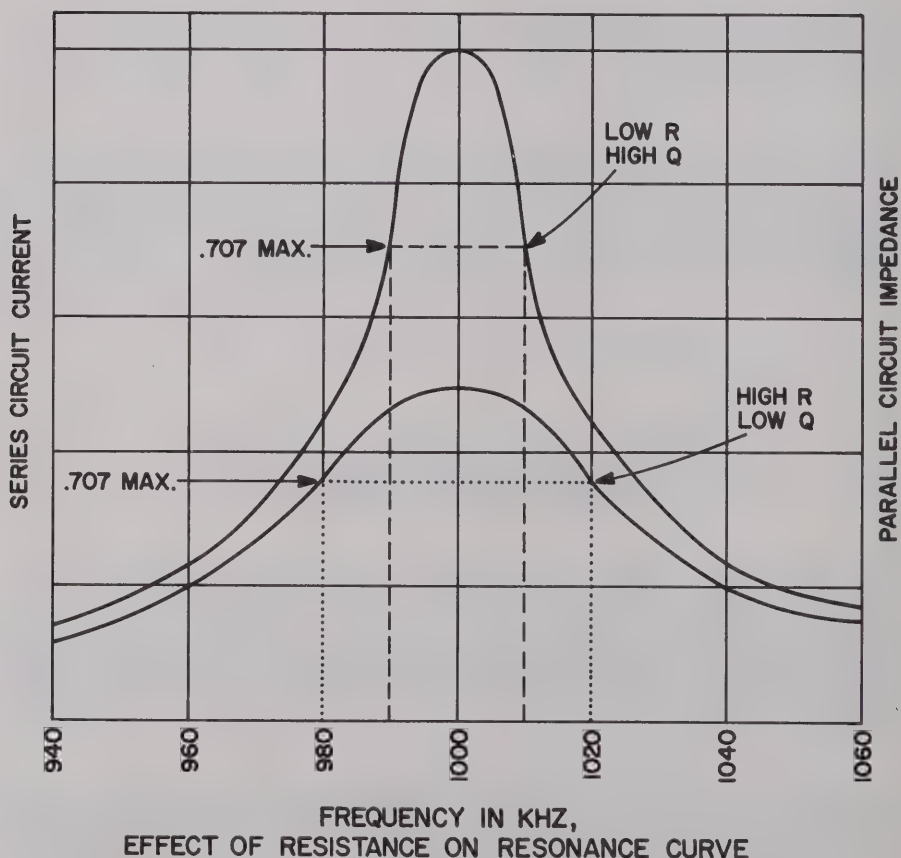


Figure 11

The following Practice Exercise questions cover the subjects which you just studied. They are:

SERIES RLC CIRCUIT ACTION

PARALLEL RLC CIRCUIT

THE FIGURE OF MERIT (Q)

EFFECT OF RESISTANCE ON RESONANCE CURVE

13. At resonance, what is the impedance of a series RLC circuit?
14. At resonance, the current in a series circuit is (a) maximum, (b) minimum.
15. In a parallel RLC circuit, what is the supply current at the resonant frequency?
16. What is the value of current within a parallel RLC circuit at resonance?
17. What is the relation between the capacitive and inductive current levels in a parallel RLC circuit at resonance?
18. Is a parallel RLC circuit capacitive or inductive at frequencies below the resonant frequency?
19. What is the impedance of a parallel RLC circuit at resonance?
20. Does resonance occur in a parallel RLC circuit when X_L equals X_C ?
21. What is represented by the Q of a coil?
22. Assume that the X_L of a coil is 2500 ohms at a particular frequency. What is the Q if the coil resistance is 100 ohms?

23. What is the impedance of a parallel RLC resonant circuit if $X_L = 3500$ ohms and $R = 50$ ohms?
24. How does the impedance of a parallel RLC circuit at resonance vary with respect to coil Q ?
25. What happens to the impedance of a series resonant RLC circuit if the coil resistance is increased?
26. What is the effect of increasing the coil resistance in a parallel resonant RLC circuit?

The effect of adding resistance in the tuned circuits causes the reduction of the "Q." Referring to Figure 11, the curve with the low Q indicates a high R and a wider bandpass, as shown by the dotted lines. The bandpass of the curve having the lower Q is from approximately 980 kHz to 1020 kHz, providing a total bandpass of about 40 kHz. This means that when the lower Q tuned circuit is resonant, its rejection of unwanted frequencies is less. For this condition, if a radio receiver is tuned to 1000 kHz and another station is operating at 1010 kHz, some of the other station's signals will be heard, even though the receiver is tuned exactly to the desired station. The interfering station causes annoying background effects.

These examples show that the width of the bandpass may be found from the resonance curve. Since the Q of a circuit determines the overall width of the resonance curve, the bandpass may also be found in terms of the resonant frequency and the Q of the circuit. This relationship can be expressed as:

$$\text{Bandpass (Hz)} = \frac{f_r}{Q} \quad (6)$$

From this relationship, it is determined that a large, or high, Q results in a narrow bandpass. Conversely, a lower Q results in a wider bandpass. This is true for both series resonant circuits and parallel resonant circuits, as shown in Figure 11. The tuned circuit having a high Q has the narrow bandpass of approximately 20 kHz.

The narrow bandpass of a high Q circuit and the wide bandpass of a low Q circuit are characteristics that may be desirable or undesirable, depending upon the circumstances. In a Standard Broadcast (AM) radio, for example, it is desirable to have a bandpass of about 20 kHz. Therefore, relatively high Q resonant circuits are used.

Later in the course, you will find that the bandpass required for proper reception of television signals is about 4 MHz (compared to the previous 20 kHz). There, the tuned circuits in a television receiver are deliberately designed to have a low Q and wide bandpass.

ANALYSIS OF A SERIES TUNED CIRCUIT

Figure 12A shows how the series RLC circuit of Figure 6 is used in practical circuits of radio and television receivers.

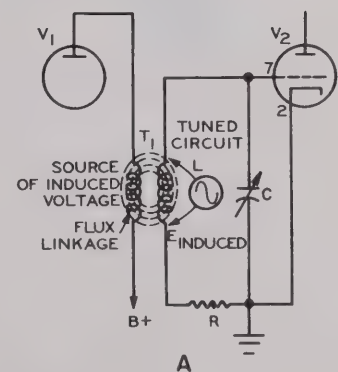


Figure 12

FREQUENCY EFFECTS ON RLC CIRCUITS

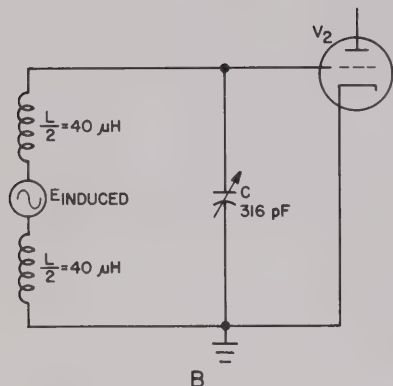
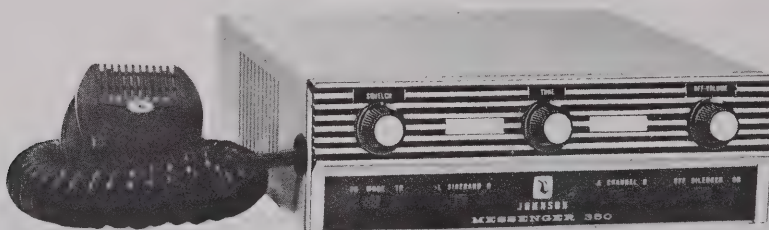


Figure
12

Assume that the plate circuit of tube V_1 carries the radio-frequency current of the desired station. This r-f current develops a changing magnetic field around the primary of T_1 . This induces a voltage into the secondary of T_1 that is effectively in series with L and C and is the source voltage. The equivalent circuit is shown in Figure 12B. Notice that the equivalent values of L and C are the same as in Figure 6 so the resonant frequency is 1000 kHz.

When capacitor C is adjusted to resonance, the current in the series tuned circuit is maximum, as indicated by the solid line curve shown in Figure 7. At resonance, then, each of the components in the series circuit (L , C and R) will have the greatest voltage developed across it. That is, when the current is maximum, the respective voltage drops across the components will be maximum, and the voltage applied between the grid and cathode of tube V_2 is maximum. The function of tube V_2 is to amplify the voltage applied to its input circuit (grid-to-cathode).



Resonant circuits are used in transceivers to prevent the transmission of undesired signals.

Courtesy E. F. Johnson Co.

At frequencies off resonance, the current in the series circuit will be smaller, and the voltage applied to the tube will be correspondingly less. In a cascade network of tuned circuits and vacuum tubes, it is often desirable to have each tuned circuit resonate at the same frequency. This is done in order to obtain the benefit of the maximum voltage being applied to the input of successive radio-frequency amplifier stages. In more technical terms, this is called ALIGNMENT, and it is the job of the technician to make certain that each tuned circuit actually resonates at the desired frequency. Receivers and transmitters are designed with an adjustable L or C component in the tuned circuits, allowing them to be varied to bring the respective tuned circuits into proper alignment.

Remember that, in Figure 12A, the resistance, R , that is shown in series with the capacitor, C , and inductance, L , is actually the resistance of the coil.

Here again, it is desirable to keep the resistance low to obtain the greatest voltage across the capacitor at the desired band of frequencies.

APPLICATION OF SERIES RESONANT CIRCUITS

The principles of series resonant circuits have many applications in radio, television, communications and various electronic fields. By making the inductance or capacitance variable, it is possible to control the resonant frequency of the circuit. In addition to station selecting or tuning, resonant circuits are used in "filter circuits." These circuits are designed to separate currents of certain frequencies from currents of other frequencies. Because of this filtering (separating) action, a resonant circuit is often called a **BAND-PASS FILTER**.

The band-pass action shown in Figure 13 is based upon variations in voltage division, resulting from changes in reactance due to changes in frequency. In Figure 13A, the RLC circuit within the dashed lines can be considered a single element having an impedance Z . The applied voltage, E_s , divides so that part of it is across Z and the remainder is across R_o . The portion of E_s across R_o is the output voltage, E_{R_o} . As in any voltage divider, the amplitudes of the respective voltages, E_Z and E_{R_o} , depend upon the relative magnitudes of Z and R_o . Although R_o remains constant, Z changes with frequency, causing corresponding changes in the voltage division, and resultant changes in the output voltage.

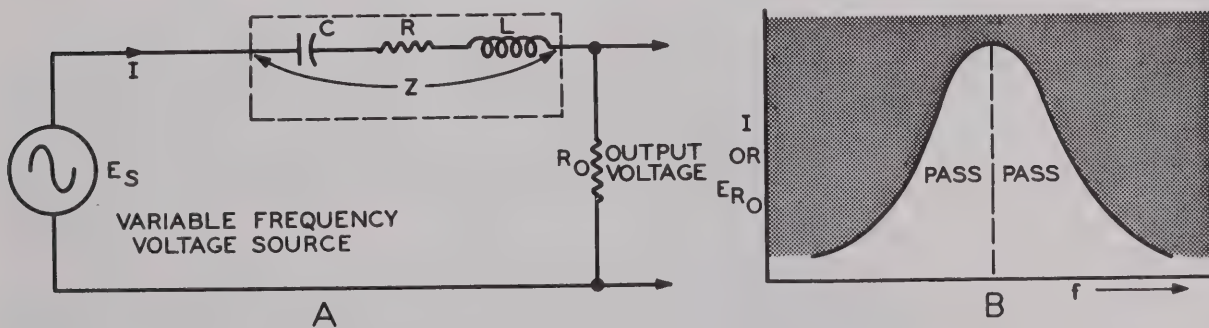


Figure 13

The RLC circuit consists of a coil and capacitor having values which enable them to be series resonant at the center frequency of the desired pass band. In Figure 13A, resistor R represents the resistance of the coil wire. At any frequency the impedance, Z , is equal to the vector sum of R and the net

reactance, X . Since X_L and X_C are equal, X is zero, and Z is minimum and equal to R . As frequency decreases from resonance, X_C increases and X_L decreases. An increase of frequency from resonance causes X_C to decrease and X_L to increase. In either case, both the net reactance and the impedance increase, as the frequency varies from resonance. When Z is larger than R_o , most of the source voltage is across the RLC circuit, and E_{R_o} is small. The reverse is true when Z is smaller than R_o .

The variations of E_{R_o} with changes in frequency are shown by the curve in Figure 13B. The resonant frequency is indicated by the vertical dashed line. At this point Z is minimum and E_{R_o} is maximum. For all frequencies above and below resonance, E_{R_o} falls off as shown. This is due to the increase of the impedance, Z , of the RLC circuit. Circuit current, I , varies similarly.

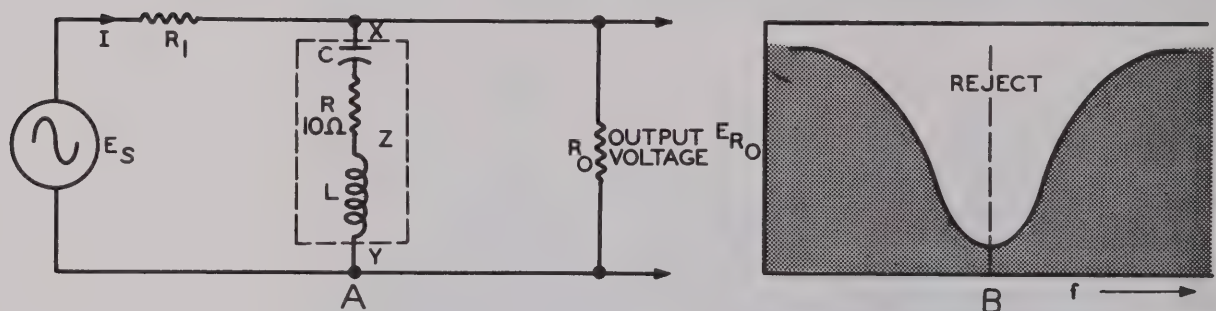


Figure 14

The same basic series resonant circuit can be placed in parallel with the output resistor, R_o , as indicated in Figure 14A. This arrangement causes the voltage E_{R_o} to vary, as shown in Figure 14B, when the values of R , R_1 and R_o are properly selected. This opposite type of response curve is due to the resonant circuit now being in parallel with the load resistor, R_o , and in series with resistor R_1 . This causes a reduction in the equivalent resistance (impedance) between points X and Y and causes most of the source voltage to be dropped across R_1 . Since R_o is in parallel with the resonant circuit, the voltage across it also has a low value. In effect, this circuit becomes a **BAND-ELIMINATION FILTER** or **BAND-REJECTION FILTER**, because the output voltages at and near resonance are reduced to low values.

EFFECT OF COUPLING ON RESONANCE CURVES

Looking at Figure 12A again, the voltage induced in the secondary of transformer T_1 is dependent, in part, on the COUPLING between the primary

and secondary windings. That is, the closer the coils are, the more flux lines from the primary cut the secondary, inducing a greater secondary voltage. If all of the flux lines of the primary cut the secondary turns, a condition known as unity coupling exists. In practical circuits, there is some flux leakage; thus, not all of the primary lines induce a voltage in the secondary. If the spacing between the coils is increased, greater leakage of flux lines exist. Fewer flux lines cause a reduction of induction in the secondary winding.

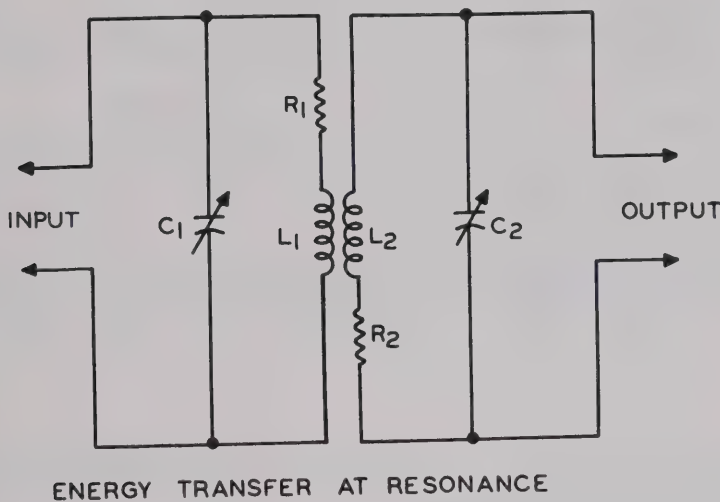


Figure 15

In the design of radio-frequency transformers, it has been found that the coupling between the windings plays an important part in the capability of the circuit to perform its desired functions. Figure 15 shows a double-tuned circuit with coupling between primary L_1 and secondary L_2 . Figure 16 shows the effect on bandpass due to the different degrees of coupling between L_1 and L_2 .

The curves of Figure 16 show the changes in the shape of the bandwidth due to changes in the amount of coupling between L_1 and L_2 . If the flux linkage is small, as for loose coupling, a smaller percentage of the magnetic lines of force of L_1 cut across the turns of L_2 . The resonance curve then has the appearance of the "loose coupling" curve.

If the coupling is tight, so that a large percentage of magnetic lines cut through inductor L_2 , the strong interaction changes the band-pass characteristics of the circuit so that the resonance curve now has two peaks, as shown

FREQUENCY EFFECTS ON RLC CIRCUITS

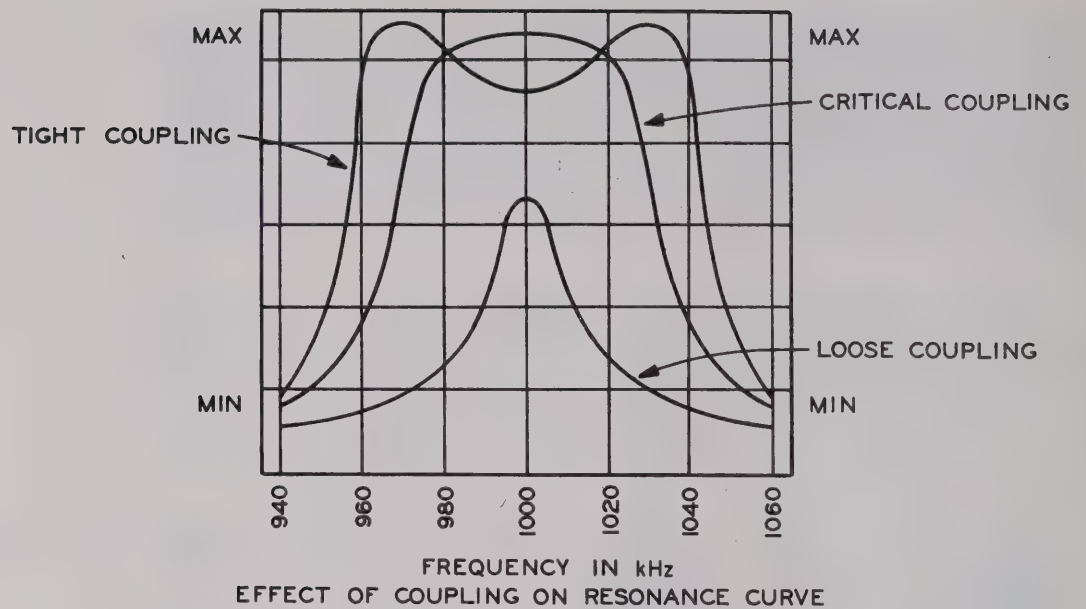
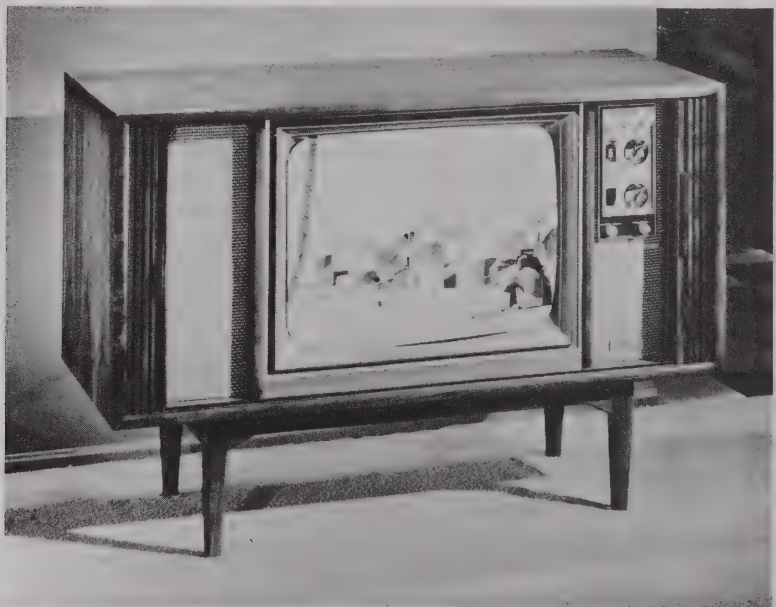


Figure 16

in the tight coupling curve. The tighter the coupling, the farther apart the peaks will appear. One peak occurs above and the other peak below the resonant frequency of the circuits.



*A modern color television uses many series and parallel resonance circuits.
Courtesy Motorola Inc.*

When adjusted between loose and tight coupling, a certain "critical coupling" value is obtained. This resonance curve has only one peak with a reasonably flat top. Thus, by designing the tuned transformer to have a specific amount of coupling, it is possible to obtain the desired response to a specific band of frequencies above and below the resonant frequency. This condition, called critical coupling, is an important consideration in radio, television and related communications circuits.

APPLICATION OF PARALLEL RESONANT CIRCUITS

The parallel tuned circuit may also be used in band-pass or band-rejection networks. Figure 17A is a simplified arrangement showing an RLC parallel circuit in series with output resistor R_o . This combination circuit is connected across a source of variable frequency voltage. Since the parallel resonant circuit presents a high impedance at the resonant frequency and a low impedance at the off-resonant frequencies, it is considered as a rejector at the resonant frequency, and an acceptor for the other frequencies.

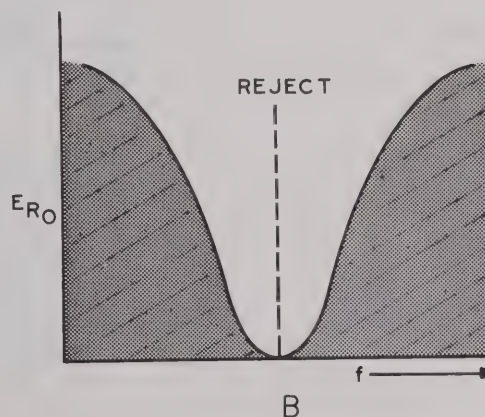
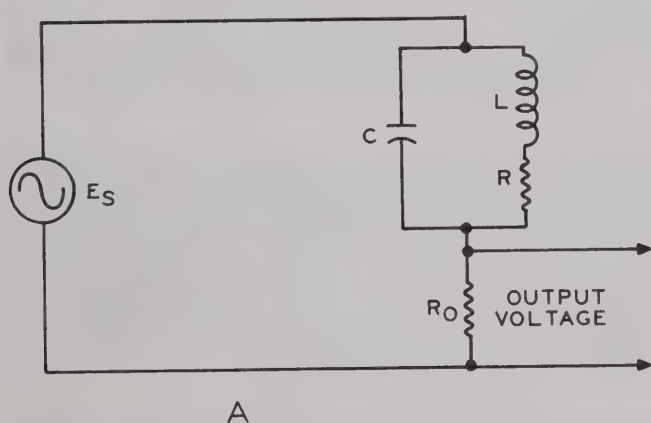


Figure 17

The circuit arrangement shown in Figure 17A functions opposite to that of the circuit shown in Figure 13A. If it is desired to reject a band of frequencies, the parallel tuned circuit is connected in series with the output circuit (R_o). The resultant output voltage curve is shown in Figure 17B. The band of frequencies at and near resonance is rejected. The only signals appearing at the output are at frequencies other than the undesired band of frequencies. Circuit arrangements similar to those shown in Figure 17A are sometimes known as "wave-traps."

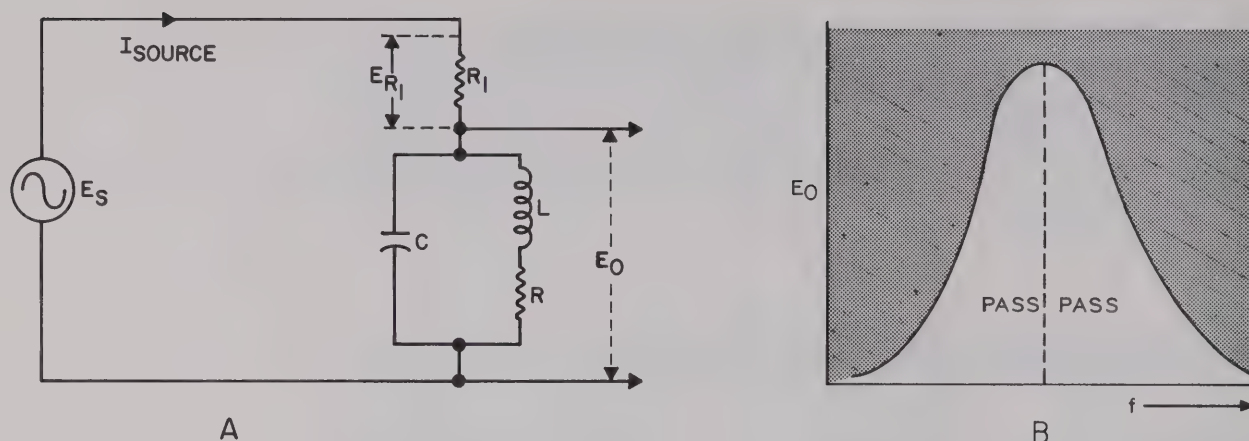


Figure 18

In Figure 18A, the arrangement is almost identical to that of Figure 17A, except that the output voltage, E_O , is now taken across the parallel tuned circuit, and the resistor in series with the tuned circuit is designated as R_1 . Notice that the voltage curve shown in Figure 18B is drawn to indicate the voltage, E_O , across the parallel tuned circuit. At resonance, the source current is minimum, as indicated by the dashed line curve of Figure 10. Also, the impedance of the tuned circuit is high, as indicated by the solid line shown in Figure 10.

In effect, the circuit of Figure 18A acts as a voltage divider. When the impedance of the tuned circuit is high (at resonance) in comparison to the resistance of R_1 , the voltage drop across the tuned circuit (E_O) will be large in comparison to the voltage drop across resistor R_1 (E_{R_1}). When the impedance of the tuned circuit is low (off resonance) in comparison to the resistance of R_1 , the voltage drop across the tuned circuit (E_O) will be low in comparison to the voltage drop across R_1 (E_{R_1}).

At all frequencies, the sum of the voltage drops must equal the applied voltage. You will remember that the rule ($E = E_O + E_{R_1}$) applies to all basic series circuits. At resonance, E_O reaches its maximum, as shown by the curve in Figure 18B. At frequencies off resonance, the impedance across the tuned circuit and the voltage across it decreases. The circuit arrangement of Figure 18A is then a band-pass circuit.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

BANDWIDTH — BANDPASS

ANALYSIS OF A SERIES TUNED CIRCUIT

APPLICATION OF SERIES RESONANT CIRCUITS

EFFECT OF COUPLING ON RESONANCE CURVES

APPLICATION OF PARALLEL RESONANT CIRCUITS

27. How does the bandpass of a resonant circuit vary with coil Q ?
28. Assume that a series RLC circuit is resonant at 500 kHz. What is the bandpass in Hz if the coil has a Q of 100?
29. Does the RLC circuit connected to the grid of V_2 in Figure 12A act as a series or a parallel resonant circuit?
30. When is the voltage applied to the grid of V_2 in Figure 12A maximum?
31. What is meant by the term "alignment"?
32. Explain how the circuit arrangement shown in Figure 13A functions as a band-pass filter.
33. How does a band-pass filter differ from a band-rejection filter?
34. Explain how the circuit arrangement shown in Figure 14A functions as a band-rejection filter.

35. How does the degree of coupling between resonant circuits affect the bandpass?
36. If you wanted a narrow bandpass, should the tuned circuits be over or under coupled?
37. Explain how the parallel resonant circuit shown in Figure 17A serves as a band-rejection filter.
38. Explain how the parallel resonant circuit shown in Figure 18A serves as a band-pass filter.

SUMMARY

The condition of resonance occurs when X_L equals X_C in either a series or parallel RLC circuit. In a series resonant circuit, the impedance at resonance is equal to the value of R . Thus, circuit current is high. Below resonance, a series RLC circuit is capacitive, and above resonance it is inductive.

At resonance, the impedance of a parallel resonant circuit is high. As a result, the current drawn from the source is low. Below resonance, a parallel RLC circuit is inductive, and above resonance the circuit is capacitive.

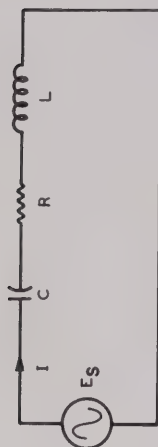
The ratio between the resistance and reactance of a coil is called its Q . The Q of a coil helps to determine the bandpass of a resonant RLC circuit. The bandpass or bandwidth is the range of frequencies which has approximately the same response as at resonance. A high Q coil and a low value of R result in a narrow bandpass while the low Q coil and high value of R result in a wide bandpass. The actual bandpass can be determined by dividing the resonant frequency by the value of Q .

One of the common uses of resonant circuits is in filter circuits. A band-pass filter is a circuit that passes a narrow band of frequencies and rejects all others. A band-rejection filter rejects a narrow band of frequencies and passes all others.

As an aid in remembering the characteristics of series and parallel RLC circuits, a summary chart is included following this summary. The basic circuit characteristics, as well as the important equations, are shown.

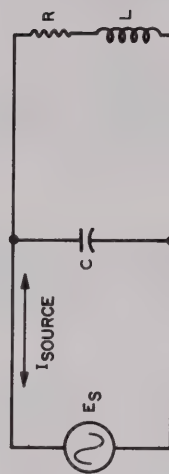
SUMMARY CHART

SERIES RESONANT CIRCUITS



FREQUENCY	VOLTAGE				CURRENT	IMPEDANCE	GENERAL COMMENT
	E_s	E_C	E_R	E_L	I		
Below Resonance	E_s lags I	E_C is greater than E_L	E_R is in phase with I	E_L is less than E_C	I leads E_s	$Z = \sqrt{R^2 + (X_C - X_L)^2}$	Circuit is capacitive.
At Resonance	E_s is in phase with I	$E_C = E_L$	E_R is in phase with I	$E_L = E_C$	I is in phase with E_s	$X_L = X_C$ Impedance is minimum $Z = R$	Circuit is resistive. The current depends upon the resistance R.
Above Resonance	E_s leads I	E_C is less than E_L	E_R is in phase with I	E_L is greater than E_C	I lags E_s	$Z = \sqrt{R^2 + (X_L - X_C)^2}$	Circuit is inductive.

PARALLEL RESONANT CIRCUITS



FREQUENCY	CURRENT	VOLTAGE		IMPEDANCE	GENERAL COMMENT
	I_{source}	E_s	E_s		
Below Resonance	I_{source} lags E_s	E_s leads I_{source}	E_s leads I_{source}	$Z_p = \frac{E_s}{I_{source}}$	Since I_L is greater than I_C if R is small, circuit is inductive. X_L is less than X_C .
At Resonance	I_{source} is minimum and is in phase with E_s	E_s is in phase with I_{source}	E_s is in phase with I_{source}	Impedance is maximum $Z = QX_L$ $Z = QX_C$	The tank current depends upon the minimum series tank resistance.
Above Resonance	I_{source} leads E_s	E_s lags I_{source}	E_s lags I_{source}	$Z = \frac{E_s}{I_{source}}$	Since I_C is greater than I_L , circuit is capacitive. X_C is less than X_L .

APPENDIX A — RESONANT FREQUENCY EQUATIONS

RESONANT FREQUENCY IN TERMS OF THE CONSTANTS OF THE TUNED CIRCUITS

At resonance,

$$X_L = X_C \text{ or } 2\pi f_r L = \frac{1}{2\pi f_r C}$$

To solve this equation for f_r , the terms are rearranged or transposed. Move the capacitive reactance terms across the “=” sign by multiplying both sides of the equation by $2\pi f_r L$:

$$(2\pi f_r L) \times (2\pi f_r C) = 1 \frac{(2\pi f_r C)}{(2\pi f_r C)}$$

Since $\frac{2\pi f_r C}{2\pi f_r C}$ equals 1, the equation reduces to: $(2\pi f_r L) \times (2\pi f_r C) = 1$.

Multiply the terms together and collect like terms:

$$(f_r \times f_r) \times (2\pi \times 2\pi) \times L \times C = 1$$

$$f_r^2 \times 4\pi^2 \times L \times C = 1.$$

Move all but the f_r^2 term across the “=” sign by dividing both sides of the equation by $4\pi^2 \times L \times C$:

$$\frac{4\pi^2 \times L \times C}{4\pi^2 \times L \times C} \times f_r^2 = \frac{1}{4\pi^2 \times L \times C}$$

Since $\frac{4\pi^2 \times L \times C}{4\pi^2 \times L \times C}$ equals 1, the equation reduces to: $f_r^2 = \frac{1}{4\pi^2 \times L \times C}$

APPENDIX A (Continued)

Extracting the square root results in:

$$\sqrt{f_r^2} = \frac{\sqrt{1}}{\sqrt{4\pi^2 LC}}$$

$$f_r = \frac{1}{2\pi \sqrt{LC}}$$

where: f_r = resonant frequency in hertz,

L = inductance in henries,

C = capacitance in farads, and

$\pi = 3.14$.

CIRCUIT CAPACITANCE IN TERMS OF INDUCTANCE AND FREQUENCY

Transpose the radical in the f_r equation by multiplying both sides by $\sqrt{LC}$:

$$f_r \sqrt{LC} = \frac{1 \sqrt{LC}}{2\pi \sqrt{LC}}$$

Since $\frac{\sqrt{LC}}{\sqrt{LC}}$ equals 1, the equation reduces to:

$$f_r \sqrt{LC} = \frac{1}{2\pi}$$

Divide both sides of the equation by f_r :

$$\frac{f_r \sqrt{LC}}{f_r} = \frac{1}{2\pi f_r}$$

APPENDIX A (Continued)

Since $\frac{f_r}{f_r} = 1$ and $\frac{1}{2\pi f_r}$ is the same as multiplying $\frac{1}{2\pi}$ by $\frac{1}{f_r}$, the equation reduces to:

$$\sqrt{LC} = \frac{1}{2\pi} \times \frac{1}{f_r}$$

$$\sqrt{LC} = \frac{1}{2\pi f_r}$$

Square both sides so that:

$$LC = \frac{1}{4\pi^2 f_r^2}$$

Divide by L so that:

$$C = \frac{1}{4\pi^2 f_r^2 L} \text{ (farads).}$$

**CIRCUIT INDUCTANCE IN TERMS OF CAPACITANCE
AND FREQUENCY**

From the previous result of squaring both sides:

$$LC = \frac{1}{4\pi^2 f_r^2}$$

Divide by C so that:

$$L = \frac{1}{4\pi^2 f_r^2 C} \text{ (henries).}$$

IMPORTANT DEFINITIONS

BANDPASS — The range of frequencies over which the response of a resonant circuit is relatively constant.

BAND-ELIMINATION FILTER — See **BAND-REJECTION FILTER**.

BAND-PASS FILTER — A circuit designed to pass a certain band of frequencies and reject frequencies above or below the designated band.

BAND-REJECTION FILTER — A circuit designed to eliminate or reject a certain band of frequencies and pass frequencies above or below the designated band. Also called a **BAND-ELIMINATION FILTER**.

COUPLING — In a double-tuned transformer, the means used to transfer signals from primary to secondary. Coupling is caused by the flux linkage between the two coils.

FIGURE OF MERIT (Q) — The ratio of the coil reactance divided by its resistance. The property which a coil has that makes it suitable for resonant circuits.

PARALLEL RESONANT CIRCUIT — A circuit consisting of a coil and capacitor connected in parallel. At resonance, it offers a high impedance to the applied signal.

RESONANT FREQUENCY — The frequency which causes the inductive reactance to be equal to the capacitive reactance in RLC circuits.

SERIES RESONANT CIRCUIT — A circuit consisting of a coil and capacitor connected in series. At resonance, it offers minimum impedance to the applied signal.

SOURCE CURRENT — The current supplied by the voltage source to a parallel RLC circuit.

ESSENTIAL SYMBOLS AND EQUATIONS

C Capacitance (farads)

f_r Resonant frequency (hertz)

L Inductance (henries)

Q Figure of merit

X_C Capacitive reactance (ohms)

X_L Inductive reactance (ohms)

X Resultant reactance (ohms)

Z_p Impedance of a parallel RLC circuit (ohms)

π 3.14

$$f_r = \frac{1}{2\pi \sqrt{LC}} \quad (1)$$

$$f_r = \frac{.159}{\sqrt{LC}} \quad (2)$$

$$Q = \frac{X_L}{R} = \frac{2\pi fL}{R} = \frac{\omega L}{R} \quad (3)$$

$$Z_p = QX_L \quad (4)$$

$$Z_p = QX_C \quad (5)$$

$$\text{Bandpass (Hz)} = \frac{f_r}{Q} \quad (6)$$

PRACTICE EXERCISE SOLUTIONS

1. (a) directly with frequency. — Inductive reactance is directly proportional to frequency, as shown by the formula $X_L = 2\pi fL$.
2. 500 ohms. — The inductive reactance would be halved from 1000 ohms to 500 ohms. Remember, inductive reactance is directly proportional to frequency.
3. In a capacitive circuit, current leads voltage while in an inductive circuit, voltage leads current.
4. (b) inversely with frequency. — Capacitive reactance is inversely proportional to frequency as shown by the formula:

$$X_C = \frac{1}{2\pi fC}$$

5. No — resistance is generally not affected by the operating frequency.
6. The resultant reactance in an LC circuit is equal to the difference between X_L and X_C .
7. 1000 ohms capacitive. — The resultant reactance is equal to the difference between X_L and X_C , 2500 ohms — 1500 ohms or 1000 ohms. (Note, the smaller number is subtracted from the larger number.) Since X_C is greater than X_L , the circuit is capacitive.
8. At the resonant frequency, X_L is equal to X_C .
9. Below the resonant frequency, X_C is greater than X_L and the circuit is capacitive.
10. A series RLC circuit is resistive at the resonant frequency where $X_L = X_C$.

$$11. f_r = \frac{1}{2\pi\sqrt{LC}} \text{ or } f_r = \frac{.159}{\sqrt{LC}}$$

PRACTICE EXERCISE SOLUTIONS (Continued)

12. 1.59 MHz. —

$$C = 100 \text{ pF} = 100 \times 10^{-12} \text{ or } 1 \times 10^{-10} \text{ farad.}$$

$$L = 100 \text{ } \mu\text{H} = 100 \times 10^{-6} \text{ or } 1 \times 10^{-4} \text{ henry.}$$

$$\begin{aligned} f_r &= \frac{.159}{\sqrt{LC}} = \frac{.159}{\sqrt{1 \times 10^{-10} \times 1 \times 10^{-4}}} = \frac{.159}{\sqrt{1 \times 10^{-14}}} \\ &= \frac{.159}{\sqrt{1 \times 10^{-7}}} = .159 \times 10^7 = 1.59 \times 10^6 \text{ Hz or } 1.59 \text{ MHz.} \end{aligned}$$

13. At resonance, the impedance of a series RLC circuit is equal to the value of resistance, since X_L cancels X_C .
14. (a) maximum. — At resonance, the impedance of a series resonant circuit is minimum, and therefore, the current is maximum.
15. At the resonant frequency, the supply or source current to a parallel resonant circuit is minimum since impedance is maximum.
16. The current is maximum in a parallel RLC circuit at resonance.
17. At resonance, X_L equals X_C , and therefore, the capacitive and inductive currents are equal.
18. At frequencies below resonance, X_L is less than X_C and thus the inductive current is greater than the capacitive current. As a result, the circuit is inductive.
19. The impedance of a parallel RLC circuit is maximum at resonance.
20. Yes — Resonance is defined as the condition when X_L equals X_C in both series and parallel RLC circuits.
21. The Q of a coil represents the ratio of reactance to resistance, $Q = \frac{X_L}{R}$.

$$22. Q = 25. \text{ — } Q = \frac{X_L}{R} = \frac{2500}{100} = 25.$$

$$23. Z = 245 \text{ k}\Omega. \text{ — } Q = \frac{X_L}{R} = \frac{3500}{50} = 70.$$

$$Z = QX_L = 70 \times 3500 = 245,000 \text{ ohms or } 245 \text{ k}\Omega.$$

PRACTICE EXERCISE SOLUTIONS (Continued)

24. The impedance of a parallel RLC circuit at resonance is directly proportional to the value of Q .
25. Increasing the coil resistance causes the impedance at resonance to increase. This, in turn, causes the current at resonance to decrease.
26. An increase of coil resistance decreases circuit Q . In turn, this decreases the impedance at resonance, increasing source current and decreasing the circuit current.
27. The bandpass of a resonant circuit is inversely proportional to Q . Increasing Q decreases bandpass, and vice versa.
28.
$$\text{Bandpass} = \frac{f_r}{Q} = \frac{500,000}{100} = 5000 \text{ Hz.}$$
29. Figure 12A is a series resonant circuit.
30. The voltage applied to the grid of V_2 is maximum at the resonant frequency.
31. "Alignment" refers to the proper tuning of the resonant circuits in electronic equipment.
32. The impedance of a series RLC circuit is minimum at resonance. Thus, at the resonant frequency, most of E_s appears across R_o . At frequencies other than resonance, more of E_s appears across the series RLC circuit and less output voltage is developed across R_o , as shown in Figure 13B.
33. A band-pass filter passes a range of signal frequencies, and a band-rejection filter blocks or rejects a range of signal frequencies.
34. In Figure 14A, the series RLC circuit is in parallel with the output. Since the impedance of a series RLC circuit is minimum at resonance, the output is shorted at the resonant frequency. At frequencies above and below resonance, the impedance of the series RLC circuit increases, thus permitting an output to appear across R_o .
35. As the degree of coupling is increased, the bandpass increases.

PRACTICE EXERCISE SOLUTIONS (Continued)

36. For a narrow bandpass, the tuned circuits should be undercoupled. Increasing the coupling increases the bandwidth.
37. In Figure 17A, the parallel RLC circuit is connected in series with the output. Since a parallel resonant circuit had maximum impedance at resonance, most of E_s appears across the parallel circuit at resonance with little output appearing across R_o . Above and below the resonant frequency, the impedance of the parallel RLC circuit decreases and almost all of E_s appears across R_o .
38. The output is taken across the parallel resonant circuit shown in Figure 18A. The output is maximum at resonance because the impedance of a parallel RLC circuit is maximum at resonance. Above and below resonance, the impedance of the parallel RLC circuit decreases and so does the output.

$$I_{max} = \frac{V_L}{R} = \frac{5 \times 10^{-3}}{1000} = 5 \times 10^{-6} \text{ A}$$



$$I = \frac{V}{R} = \frac{10}{1000} = 0.01 \text{ A}$$

$$\frac{5}{1000}$$

$$\frac{R}{2}$$

$$I = \frac{V}{R} = \frac{10}{1000} = 0.01 \text{ A}$$



EXAMINATION
CHECK SHEET

1064A

1. B - IN AN INDUCTIVE CIRCUIT, AN INCREASE OF FREQUENCY CAUSES -- AN INCREASE IN INDUCTIVE REACTANCE.

Inductive reactance is directly proportional to frequency, $X_L = 2\pi fL$.

2. C - IN A CAPACITIVE CIRCUIT, AN INCREASE OF FREQUENCY CAUSES -- A DECREASE IN CAPACITIVE REACTANCE.

Capacitive reactance is inversely proportional to frequency. $X_C = 1/2\pi fC$.

3. C - IN A SERIES CIRCUIT CONTAINING INDUCTIVE AND CAPACITIVE REACTANCE AND RESISTANCE, A CONDITION OF RESONANCE EXISTS WHEN -- X_L EQUALS X_C .

Resonance occurs in both series and parallel RLC circuits when X_L equals X_C . At resonance, the phase shift developed by the capacitance cancels that developed by the inductance.

4. D - AT RESONANCE, THE IMPEDANCE OF A SERIES RLC CIRCUIT IS EQUAL TO -- R.

At resonance, the effects of X_L and X_C cancel and the impedance is equal to the value of R.

5. B - A PARALLEL RLC CIRCUIT AT RESONANCE HAS -- MAXIMUM CIRCULATING CURRENT.

At resonance, the impedance of a parallel RLC circuit is maximum. As a result the source current is minimum. However, the circulating current is maximum.

6. A - A SERIES TUNED CIRCUIT WITH A HIGH Q MEANS THAT IT -- HAS A NARROW BANDPASS.

The bandpass or bandwidth is inversely proportional to the value of Q. A high Q circuit has a narrow bandpass and vice versa.

7. B - AT FREQUENCIES BELOW RESONANCE, A SERIES RLC CIRCUIT -- IS CAPACITIVE.

Below resonance X_C is greater than X_L . In a series circuit, the greater value of reactance determines the type of circuit.

8. B - WHAT IS THE RESONANT FREQUENCY OF A PARALLEL RLC CIRCUIT IF L EQUALS $150 \mu\text{H}$ AND C EQUALS 300 pF ? -- 750 kHz.

To determine the resonant frequency, use Equation (1a).

$$\begin{aligned} f_r &= \frac{.159}{\sqrt{LC}} = \frac{.159}{\sqrt{150 \times 10^{-6} \times 300 \times 10^{-12}}} \\ &= \frac{.159}{\sqrt{1.5 \times 10^{-4} \times 3 \times 10^{-10}}} = \frac{.159}{\sqrt{4.5 \times 10^{-14}}} = \frac{.159}{2.12 \times 10^{-7}} \\ &= .075 \times 10^7 \text{ or } 750 \text{ kHz.} \end{aligned}$$

9. D - WHAT IS THE BANDPASS OF A CIRCUIT RESONANT AT 500 kHz IF THE VALUE OF X_C IS $2.5 \text{ k}\Omega$ AND THE COIL RESISTANCE IS 25 OHMS? -- 5000 Hz.

Since $X_L = X_C$ at resonance, X_L is also $2.5 \text{ k}\Omega$. The value of Q is found by using Equation 3

$$Q = \frac{X_L}{R} = \frac{2500}{25} = 100$$

The bandpass is then found by employing Equation 6

$$\text{Bandpass} = \frac{f_r}{Q} = \frac{500,000}{100} = 5000 \text{ Hz.}$$

10. A - A PARALLEL RESONANT CIRCUIT HAS AN INDUCTIVE REACTANCE OF 10,000 OHMS AND A COIL RESISTANCE OF 200 OHMS. WHAT IS THE IMPEDANCE? -- 500,000 OHMS.

The Q is found using Equation 3.

$$Q = \frac{X_L}{R} = \frac{10,000}{200} = 50$$

The impedance is found using Equation 4

$$Z = QX_L = 50 \times 10,000 = 500,000 \text{ ohms}$$

EXPERIMENT 2

RESONANT CIRCUITS

PARTS NEEDED

- | | |
|--|-------------------------------|
| 1 - Complete Design Console | 1 - .1 μ F Disk Capacitor |
| 1 - Multimeter with Test Leads and Spring Adapters | 1 - 400 Ω Relay |
| 1 - 4.7 k Ω , 1/2 W, 20% Resistor | 4 - Modular Connectors |
| 1 - 10 k Ω , 1/2 W, 20% Resistor | - No. 22 Solid Hookup Wire |

OBJECTIVE

Resonance is defined as the condition in a simple series or parallel LC circuit when the frequency is such that $X_L = X_C$. At resonance, the circuit appears purely resistive. In this experiment you will investigate the action of series and parallel LC resonant circuits. Your measurements will illustrate the specific voltage, current and impedance conditions that exist in series and in parallel resonant circuits.

PART 1

PROCEDURE

SERIES RESONANT CIRCUITS

1. Set up the circuit of Figure 2-1 on your design console. Use the audio generator sinewave output. Note that the relay coil is used as the inductance.
2. Turn on the design console. The ADJUST VOLTAGE control can be set fully counterclockwise since the low voltage power supply is not used in this experiment.
3. Set the ADJUST FREQ. control to 0; and measure the voltage drops across L_1 , C_1 and R_1 . Record these values in the chart of Figure 2-2. Use the output function on your multimeter for these ac voltage measurements.
4. The circuit current is computed by using the voltage drop across R_1 and Ohm's Law as shown below:

$$I_T = \frac{E_{R_1}}{R_1}$$

Compute the value of circuit current for an ADJUST FREQ. control setting of 0,

and record it in the chart of Figure 2-2.

5. Complete the chart of Figure 2-2 by setting the ADJUST FREQ. control to each of the indicated numbers in the left column. Record the corresponding values of E_{R_1} , E_{C_1} and E_{L_1} .

6. Using the data recorded in the chart of Figure 2-2, draw curves representing E_{C_1} and E_{L_1} versus frequency on the graph of Figure 2-3. Be sure to label the curves for E_{C_1} and for E_{L_1} so that you can analyze the data. Also draw a curve showing the circuit current (I_T) versus frequency on the graph of Figure 2-4. Your voltage graph (Figure 2-3) should look similar to that shown in Figure 2-5, and the current graph (Figure 2-4) should be similar to the one shown in Figure 2-6.

CONCLUSION

The graphs you prepared in Figure 2-3 and 2-4 should illustrate the basic characteristics of a series resonant circuit. At resonance, the impedance of a series LC circuit is at minimum. Thus, the circuit current is at maximum at resonance. Your graph of Figure 2-4 should show a peak at some point. On either side of resonance, the impedance increases and the circuit current decreases. There may be some difference between the resonant point in Figure 2-3 (where $E_{L_1} = E_{C_1}$) and the resonant point in Figure 2-4 where I_T is at maximum. This is caused by meter loading.

At resonance, the circuit appears resistive since $X_L = X_C$. However, at either side of resonance, the circuit has reactance as well as resistance. Below resonance, X_C is greater than X_L . Thus, the circuit is capacitive; and the voltage across C should be greater than the voltage across L. Above resonance, X_L is greater than X_C . As a result, the circuit is inductive; and the voltage across L should be greater than that across C.

PART 2

PROCEDURE

PARALLEL RESONANT CIRCUITS

1. Set up the circuit shown in Figure 2-7 on your design console. As in the previous circuit, the relay coil is used as the inductance. Use the audio generator sinewave output.
2. Turn on the design console and set the ADJUST VOLTAGE control fully counterclockwise since the low voltage power supply is not used.
3. Set the ADJUST FREQ. control to 0. Measure the ac voltage drop across

Resonant Circuits

R_1 and record it in the chart of Figure 2-8. R_1 is connected in series with the parallel LC circuit to provide a means of measuring the circuit current. Use the output function of your multimeter to measure this ac voltage.

4. Calculate the circuit current by using the voltage drop across R_1 and Ohm's Law.

$$I_T = \frac{E_{R_1}}{R_1}$$

Record the value in the chart of Figure 2-8.

5. Complete the chart of Figure 2-8 for each of the ADJUST FREQ. control settings.

6. Using the values of I_T from the chart of Figure 2-8, plot a curve showing I_T versus frequency on the graph of Figure 2-9. Your curve should have the general appearance of that shown in Figure 2-10.

CONCLUSION

The impedance of a parallel circuit at resonance is at maximum and the source current is at minimum. This should be verified by your graph of Figure 2-9.

At resonance, the circuit is resistive. Below resonance, the circuit is inductive since X_L is less than X_C ; and thus the inductive current is greater than the capacitive current. Above resonance, X_C is less than X_L (the circuit is capacitive). Note that these conditions are opposite to those in the series resonant circuit.

NOTES

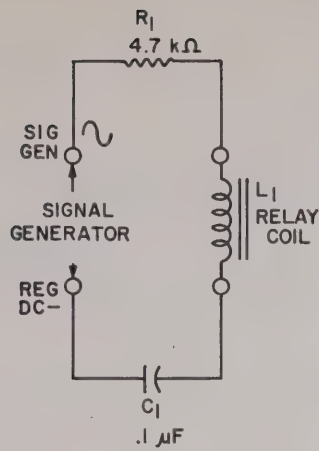


FIGURE 2-1

FREQ.	E_{C1}	E_{L1}	E_{R1}	I_T
0	3.0	1.8	2.4	.51
1	3.0	1.8	2.3	.49
2	3.0	1.8	2.3	.49
3	2.9	1.9	2.4	.51
4	2.8	2.0	2.5	.53
5	2.6	2.2	2.5	.53
6	2.3	2.5	2.6	.55
7	1.8	2.8	2.6	.55
8	.7	2.9	1.4	.30
9	0	0	0	0
10	0	0	0	0

FIGURE 2-2

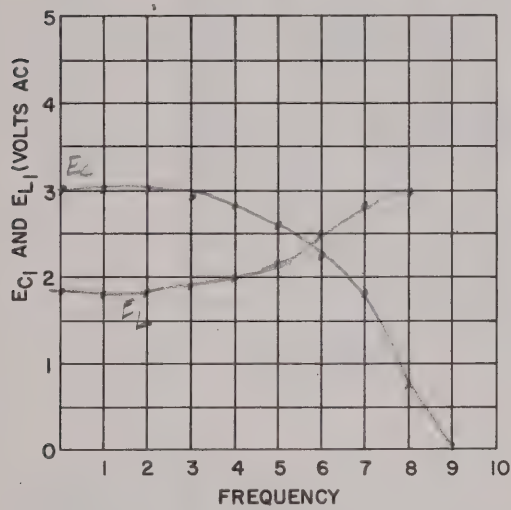


FIGURE 2-3

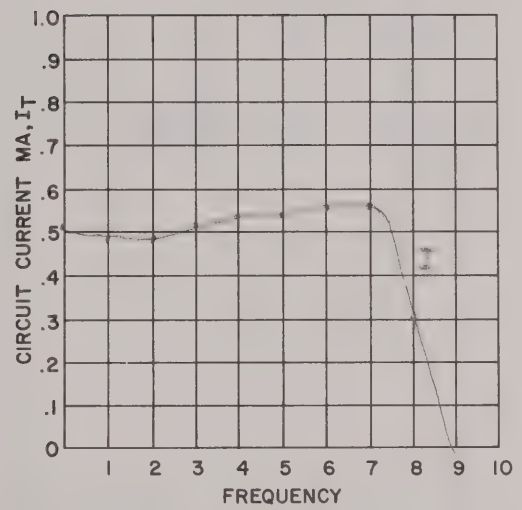


FIGURE 2-4

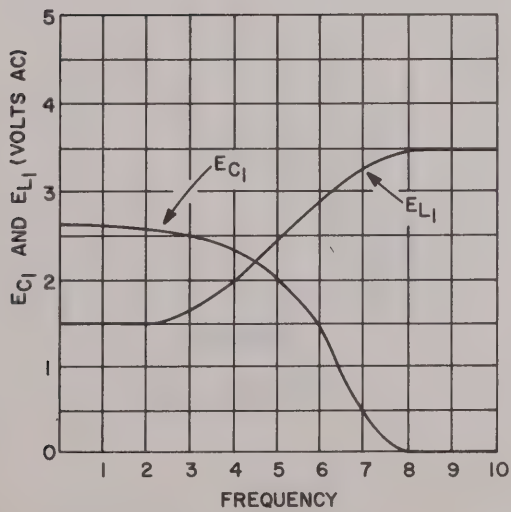


FIGURE 2-5

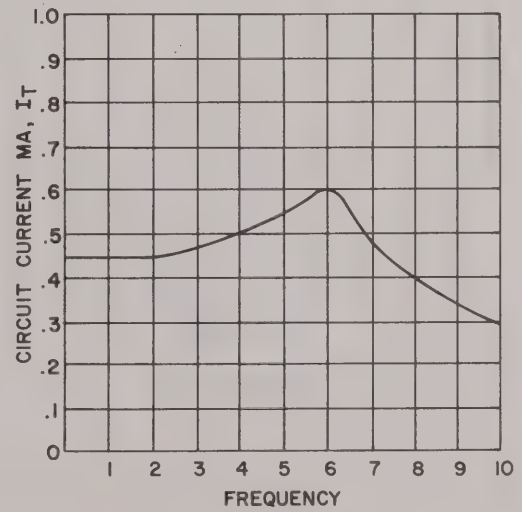


FIGURE 2-6

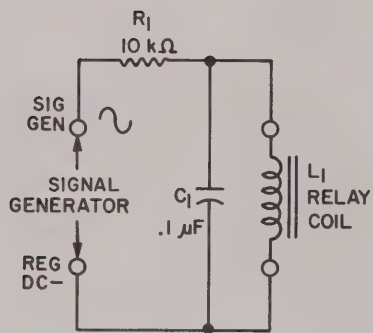


FIGURE 2-7

FREQ.	E_{R_1}	I_T
0	.3	
1	.4	
2	.4	
3	.4	
4	.3	
5	.3	
6	.4	
7	.4	
8	.5	
9	0	
10	0	

FIGURE 2-8

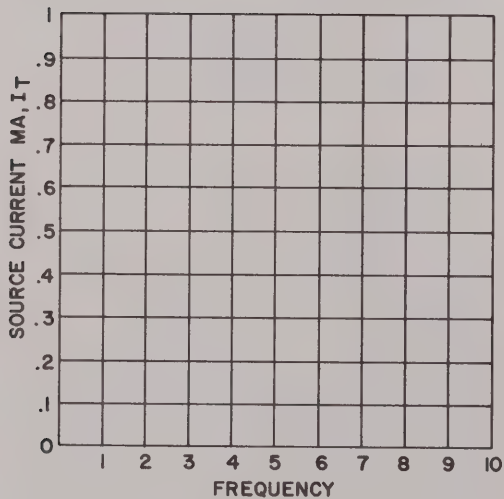


FIGURE 2-9

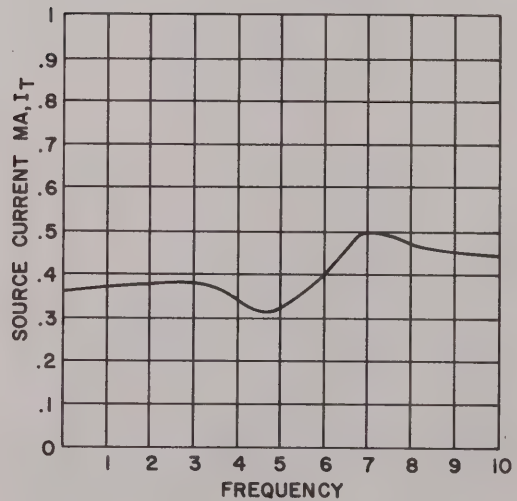


FIGURE 2-10



ONE OF THE

BELL & HOWELL SCHOOLS

9506-2A
EXAMINATION
CHECK SHEET

1. D - AT RESONANCE, THE IMPEDANCE OF A SERIES LC CIRCUIT IS -- AT MINIMUM.
At resonance, a series LC circuit appears purely resistive since $X_L = X_C$. Due to the cancelling effects of X_L and X_C , circuit impedance is at minimum, resulting in maximum current.
2. C - AT RESONANCE, THE CURRENT IN A SERIES LC CIRCUIT IS -- AT MAXIMUM.
Refer to the solution for Question 1 above.
3. D - BELOW RESONANCE IN A SERIES LC CIRCUIT, -- X_C IS GREATER THAN X_L .
Below resonance, X_C is greater than X_L . As a result, E_C is greater than E_L ; and the circuit appears capacitive.
4. B - IN A PARALLEL LC CIRCUIT, -- $E_L = E_C$.
In a parallel circuit, the capacitor and inductor voltages are always equal, at any frequency. The value of inductive and capacitive currents, however, varies with frequency.
5. A - THE IMPEDANCE OF A PARALLEL LC CIRCUIT AT RESONANCE IS -- MAXIMUM.
At resonance, the capacitive and inductive currents cancel since $X_L = X_C$. Thus, source current is minimum; and circuit impedance is maximum.

AC POWER

1067





The power output of a single sideband transceiver is generally given in terms of peak power. This particular unit has a peak output of 100 watts.

Courtesy KAAR Electronics Corp.

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Power in Capacitive Circuits	Page 8
True and Apparent Power	Page 8
Power Equations	Page 12
Power Factor	Page 13

*He who is silent is forgotten;
he who abstains is taken at his word;
he who does not advance falls back;
he who stops is overwhelmed, distanced, crushed;
he who ceases to grow greater becomes smaller;
he who leaves off, gives up;
the stationary condition is the beginning of the end.
—Amiel*

AC POWER

Man uses electric energy in many ways. Electric lamps provide light for homes, factories, offices and streets. Electric heating elements are used in toasters, coffee makers and electric irons. Heating equipment is used in industry to make plywood, form plastics and treat metals. Electric motors are used in household appliances, automobiles and industrial equipment. Transmitters and receivers are used to convey messages and provide entertainment. These are but a few of the many uses of electric energy.

In giving the rating of an electrical device, it is common to give not only the voltage at which it operates, but also the rate at which it produces or uses electric energy. The rate of producing or using electric energy is called **POWER** and is measured in watts. For example, an incandescent lamp may be rated at 50 watts at 120 volts; a generator may be rated at 1000 kilowatts at 600 volts; and a motor may be rated at 1/2 horsepower at 120 volts, where 1 horsepower equals about 746 watts.

POWER IN RESISTIVE CIRCUITS

In an ac circuit, the instantaneous power is equal to the instantaneous current times the instantaneous voltage. In the form of an equation:

$$p = ei \quad (1)$$

where: p is the instantaneous power in watts,

e is the instantaneous voltage in volts, and

i is the instantaneous current in amperes.

NOTE: p , e and i are lower case since they represent instantaneous values.

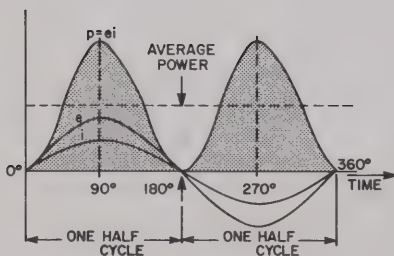


Figure
1

Figure 1 shows the relationship between e , i and p for a purely resistive ac circuit. In Figure 1, 0 degrees through 360 degrees is in reference to the voltage and current sinusoidal waveshapes. The power curve is plotted by multiplying the instantaneous voltage and current and is a sinewave that has twice the frequency of the voltage and current waveforms that are shown in Figure 1.

In purely resistive circuits, the power curve lies above the horizontal reference axis at all times. During the first half cycle of the voltage and current sinusoidal waveforms, both e and i are positive and their product (ei) is a positive power. In the second half cycle, both e and i are negative and again their product is a positive power (if two quantities have the same sign, their product is positive). This means that the resistor absorbs power and dissipates heat during all portions of the cycle.

The maximum height of the power curve, or the **PEAK POWER**, is the product of the **PEAK VOLTAGE** and **PEAK CURRENT**. In the form of an equation:

$$P_{\text{peak}} = E_{\text{peak}} I_{\text{peak}} \quad (2)$$

where: P_{peak} is the peak power in watts,

E_{peak} is the peak voltage in volts, and

I_{peak} is the peak current in amperes.

The average power, shown by the lower dashed line in Figure 1, is one-half of the peak power. The shaded portion above the dashed line just fills in the unshaded portion below the dashed line. In the form of an equation:

$$P_{\text{ave}} = \frac{E_{\text{peak}} I_{\text{peak}}}{2} = \left(\frac{E_{\text{peak}}}{1.414} \right) \left(\frac{I_{\text{peak}}}{1.414} \right) \quad (3)$$

Since $E_{\text{peak}}/1.414$ and $I_{\text{peak}}/1.414$ are effective (or rms) values (remember, $\text{peak} \div 1.414 = \text{rms}$), the **AVERAGE POWER** in a circuit containing only resistance equals the **EFFECTIVE VOLTAGE** times the **EFFECTIVE CURRENT** of the circuit. In the form of an equation:

$$P_{\text{ave}} = E_{\text{RMS}} \times I_{\text{RMS}} \quad (3a)$$

Since the average power is $1/2$ of the peak power, the peak power is twice the average power:

$$P_{\text{peak}} = 2P_{\text{ave}} \quad (3b)$$

Effective current and effective voltage produce the same amount of heat in a resistor as equal values of direct current and voltage.

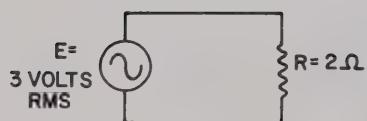
THUS, AVERAGE AC POWER IN A PURELY RESISTIVE CIRCUIT IS EQUIVALENT TO THE DC POWER PRODUCED BY A DIRECT CURRENT AND VOLTAGE EQUAL IN VALUE TO THE EFFECTIVE ALTERNATING CURRENT AND VOLTAGE.

Unless otherwise stated, the term power in an ac circuit usually refers to the average power in the circuit.



The instrument shown above is used to read instantaneous power in radio-frequency circuits.

Courtesy Hewlett-Packard Co.



*Figure
2*

An example of a purely resistive circuit is shown in Figure 2. The current is:

$$I = \frac{E}{R} = \frac{3}{2} = 1.5 \text{ amperes, rms.}$$

The peak voltage and current are:

$$E_{\text{peak}} = E_{\text{RMS}} \times 1.414 = 3 \times 1.414 = 4.24 \text{ volts}$$

$$I_{\text{peak}} = I_{\text{RMS}} \times 1.414 = 1.5 \times 1.414 = 2.12 \text{ amperes.}$$

Then the peak and average power are:

$$\begin{aligned} P_{\text{peak}} &= E_{\text{peak}} \times I_{\text{peak}} \\ &= 4.24 \times 2.12 = 9 \text{ watts.} \end{aligned}$$

$$\begin{aligned} P_{\text{ave}} &= E_{\text{RMS}} \times I_{\text{RMS}} \\ &= 3 \times 1.5 = 4.5 \text{ watts.} \end{aligned}$$

Remember that P_{peak} is twice P_{ave} .

POWER IN INDUCTIVE CIRCUITS

Figure 3 shows the relationship between e , i and p for a purely inductive ac circuit. In a purely inductive circuit, the current lags the voltage by 90 degrees.

As in Figure 1, the power curve of Figure 3 is plotted by multiplying the instantaneous voltage and current. Whenever either the voltage or current is zero (0 degrees, 90 degrees, 180 degrees, 270 degrees and 360 degrees), the power is zero. Between 0 degrees and 90 degrees, the current is negative and the voltage is positive. Therefore, their product is negative (if two quantities have opposite signs, their product is negative). Between 90 degrees and 180 degrees both the current and voltage are positive and their product is positive. Similarly, the power curve is negative between 180 degrees and 270 degrees and positive between 270 degrees and 360 degrees.

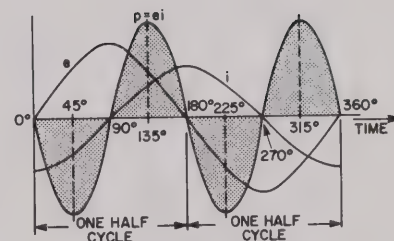


Figure
3

THE POSITIVE PORTIONS OF THE POWER CURVE REPRESENT THE PERIODS DURING WHICH THE INDUCTANCE IS ABSORBING ENERGY FROM THE SOURCE BY BUILDING UP A MAGNETIC FIELD. THE NEGATIVE PORTIONS OF THE POWER CURVE REPRESENT PERIODS DURING WHICH THE INDUCTANCE IS RETURNING THE STORED ENERGY TO THE SOURCE AS THE MAGNETIC FIELD COLLAPSES.

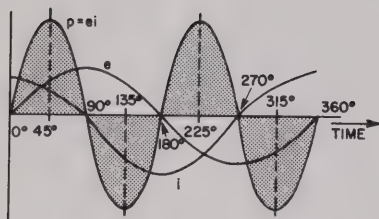
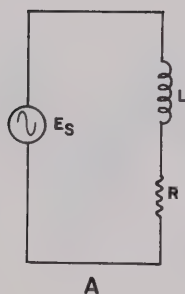


Figure 4

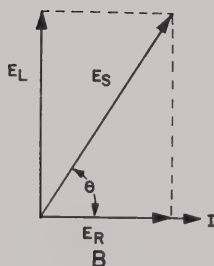
NO POWER IS DISSIPATED IN A PURELY INDUCTIVE CIRCUIT.

POWER IN CAPACITIVE CIRCUITS

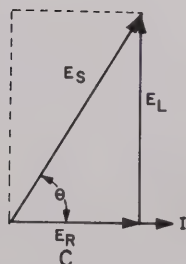
Figure 4 shows the relationship between e , i and p for a purely capacitive ac circuit. In a purely capacitive circuit, the current leads the voltage by 90 degrees.



A



B



C

Figure 5

As in Figures 1 and 3, the power curve of Figure 4 is plotted by multiplying the instantaneous voltage and current. The positive portions of the power curve represent the periods during which the capacitor is charging and storing energy in an electric field. The negative portions of the power curve represent the periods during which the capacitor is discharging and returning the stored energy to the source.

The average power of Figure 4 is zero. The shaded portion above the horizontal reference line is equal to the shaded portion of the power curve below the horizontal reference line. The power taken from the source during one quarter of a cycle is returned to the source during the next quarter cycle. Thus:

NO POWER IS DISSIPATED IN A PURELY CAPACITIVE CIRCUIT.

TRUE AND APPARENT POWER

Figure 5A is the schematic diagram of a series circuit containing both resistance and inductance. Figure 5B is a vector diagram showing the phase relation between the three voltages and the current in this circuit. In Figure 5C, the E_L vector has been moved over as shown to form an impedance

The following Practice Exercise questions cover the subjects which you have just studied. They are:

POWER IN RESISTIVE CIRCUITS

POWER IN INDUCTIVE CIRCUITS

POWER IN CAPACITIVE CIRCUITS

1. What does the power rating of an electrical device indicate?
2. In a purely resistive circuit the voltage (a) is in phase with the current, (b) lags the current, (c) leads the current.
3. The equation for instantaneous power in an ac circuit is (a) $p = ei$, (b) $p = e/i$, (c) $p = i/e$.
4. For most practical purposes, an electric toaster is purely resistive. Therefore, the instantaneous power in a toaster is always positive. True or False?
5. During normal operation a certain electric toaster dissipates 1000 watts. This figure represents (a) peak power, (b) average power, (c) $1/2$ average power.
6. An incandescent lamp has a voltage of 120 volts effective across it and draws a current of .5 ampere effective. What is the value of average power and peak power?
7. With a sinewave input, a certain audio amplifier has an average power output of 10 watts. What is the peak power output of this amplifier at the peaks of the input signal?

8. In a purely inductive circuit, the power that is absorbed from the source during one portion of the cycle is returned to the source during the next portion of the cycle. True or False?
9. The power supplied to a pure inductance is dissipated in the form of heat, just as in a resistance. True or False?
10. The wattmeter at the service entrance to a certain factory indicates the accumulated average power dissipated by the factory. The electric power company servicing the factory observed that the factory requires a much larger current than that indicated by the wattmeter. Could highly inductive loads cause this condition?
11. The average power in a purely capacitive circuit is (a) zero, (b) one-half of the peak power, (c) equal to the peak power.

triangle. This is essentially the same as is done to find the resultant vector. The voltage across the resistance, E_R , is in phase with the circuit current, I . The voltage across the inductance, E_L , leads the circuit current by 90 degrees. The source voltage, E_s , is the vector sum of E_R and E_L and leads the circuit current by the angle θ .

Figure 6 shows the power curve for the circuit of Figure 5A. In purely resistive, inductive and capacitive circuits, the instantaneous power is the product of the instantaneous voltage and current. In a circuit containing both resistance and inductance, some of the power absorbed from the source is dissipated by the resistance, and the remainder is stored in the magnetic field of the inductance and returned to the source later in the cycle. Thus, a greater portion of the power curve is above the horizontal reference axis than below it.

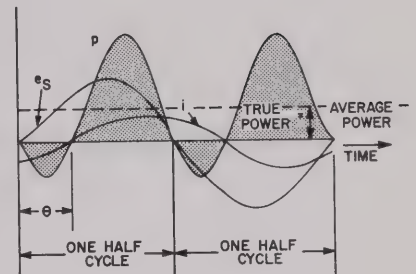
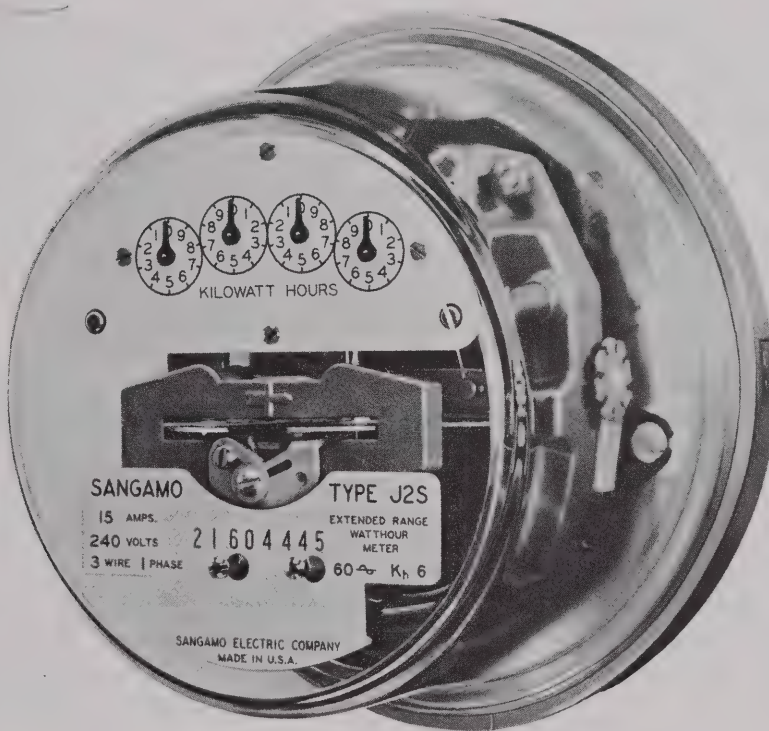


Figure 6



Watthour meters, like the one shown above, are used to measure the total power consumption in homes and factories.

Courtesy Sangamo Electric Co.

All of the power taken from the source is dissipated as heat in a **PURELY RESISTIVE** circuit. This dissipated power is the product of the effective voltage and the effective current, and is called **TRUE POWER (P_{true})**, measured in **WATTS (W)**. As shown in Figure 6, true power is equal to average power.

In an ac circuit containing both resistance and reactance, the product of the effective voltage and effective current DOES NOT give the dissipated power, because part of the power is returned to the source. (Remember, energy is stored in an inductor or capacitor during part of the cycle and returned during another part of the cycle.) To distinguish it from the true power, the product of effective voltage and effective current in a circuit containing BOTH RESISTANCE AND REACTANCE is called **APPARENT POWER** (P_{apparent}), measured in **VOLTAMPERES (VA)**.

In the circuit of Figure 5A, the product of E_R and I gives the true power. The product of E_L and I is called **REACTIVE POWER** (P_{reactive}). Reactive power is measured in **VOLTAMPERES-REACTIVE (var)**.

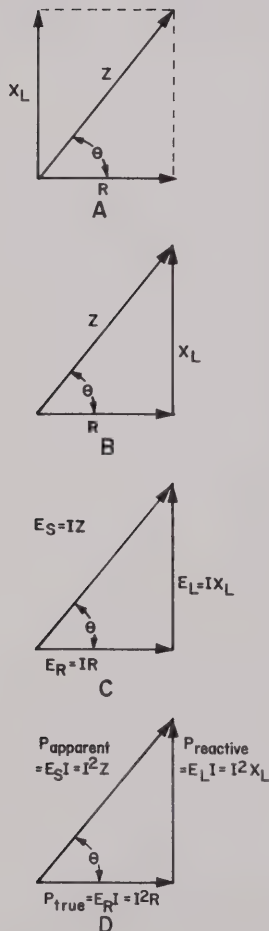


Figure 7

Figure 7A shows the impedance vectors for a series circuit with inductance and resistance. In Figure 7B, the X_L vector is moved to the right to form an impedance triangle. The voltage triangle of Figure 7C is produced from the impedance triangle by multiplying R , X_L and Z by the circuit current, I . Finally, the **POWER TRIANGLE** of Figure 7D is produced by multiplying E_S , E_L and E_R by I . The same power triangle can be produced by multiplying each side of the impedance triangle (R , X_L and Z) by I^2 . Figure 7D also shows us that the apparent power is the vector sum of the true power and the reactive power.

An important point to remember in connection with the power triangle of Figure 7D is that no reactive power is dissipated by the circuit. Only the true power part of the apparent power is dissipated by the circuit.

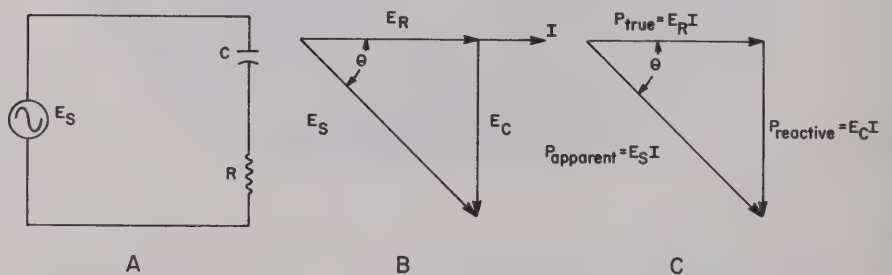


Figure 8

Figure 8A is the schematic diagram of a series circuit containing both resistance and capacitance. Figure 8B shows the phase relationships between the voltages and current of this circuit in the form of a vector diagram. The

voltage across the resistance, E_R , is in phase with the circuit current, I . The voltage across the capacitance, E_C , lags the circuit current by 90 degrees. The source voltage, E_S , is the vector sum of E_R and E_C , and lags the circuit current by the angle θ .

Figure 8C is the power triangle for the circuit of Figure 8A. The apparent power (VA) is the vector sum of the true power (W) and the reactive power (var). Again, the true power is the only power dissipated by the circuit. All of the reactive power is returned to the source.

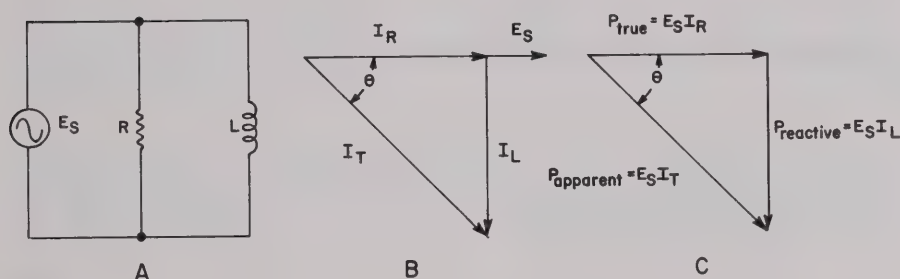


Figure 9

Figure 9A is the schematic diagram of a parallel circuit containing both resistance and inductance. Figure 9B shows the phase relationship between the currents and the voltage in this circuit in the form of a vector diagram. The current through the resistance, I_R , is in phase with the source voltage, E_S . The current through the inductance, I_L , lags the source voltage by 90 degrees. The total current, I_T , which is the vector sum of I_R and I_L , lags the source voltage, E_S , by the angle θ . Figure 9C is the power triangle for the circuit of Figure 9A. The power triangle is produced by multiplying each side of the current triangle of Figure 9B by the source voltage, E_S . The apparent power (VA) is the vector sum of the true power (W) and the reactive power (var).

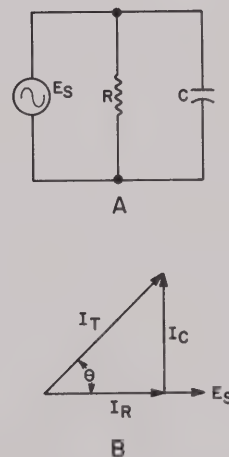


Figure 10A is the schematic diagram of a parallel circuit containing both resistance and capacitance. Figure 10B shows the phase relationships between the currents and voltage in this circuit in the form of a vector diagram. The current through the resistance, I_R , is in phase with the source voltage, E_S . The current through the capacitance, I_C , leads the source voltage by 90 degrees. The total current, I_T , which is the vector sum of I_R and I_C , leads the source voltage, E_S , by the angle θ . Figure 10C is the power triangle for the circuit of Figure 10A. The apparent power (VA) is the vector sum of the true power (W) and the reactive power (var).

Figure 10

POWER EQUATIONS

As previously stated, true power is the product of the voltage across the resistance of a circuit and the current through the resistance. Stated as an expression:

$$P_{\text{true}} = E_R I_R \quad (4)$$

where: E_R is the voltage across the resistance, and

I_R is the current through the resistance.

This equation also applies to dc circuits. True power is the same as average power.

According to Ohm's Law, $E_R = I_R R$ and $I_R = E_R / R$. Substituting for E_R and I_R in Equation 4 gives:

$$P_{\text{true}} = I_R^2 R \quad (4a)$$

$$= \frac{E_R^2}{R} \quad (4b)$$

As shown in Figure 6, the average and true powers are equal:

$$P_{\text{true}} = P_{\text{ave}} \quad (4c)$$

Similarly, for reactive power and apparent power:

$$P_{\text{reactive}} = E_X I_X \quad (5)$$

$$= I_X^2 X \quad (5a)$$

$$= \frac{E_X^2}{X} \quad (5b)$$

and

$$P_{\text{apparent}} = E_S I_T \quad (6)$$

$$= I_T^2 Z \quad (6a)$$

$$= \frac{E_S^2}{Z} \quad (6b)$$

The following Practice Exercise questions cover the subject which you have just studied. It is:

TRUE AND APPARENT POWER

12. True power is measured in (a) watts, (b) ohms, (c) amperes.
13. Apparent power is measured in (a) voltamperes, (b) ohms, (c) amperes.
14. In a purely resistive circuit the apparent power equals the true power. True or False?
15. An ac motor contains both inductance and resistance. Is the product of effective voltage and effective current equal to the true power in such a circuit?
16. What is the unit of reactive power?
17. In a purely reactive circuit, the apparent power equals the (a) true power, (b) reactive power.
18. The apparent power in an ac circuit containing both resistance and reactance is the vector sum of what two components?
19. In a power triangle, the two legs of the triangle represent the true power and reactive power, and the hypotenuse represents the (a) apparent power, (b) average power.

20. Which part of a power triangle represents the power dissipated by a circuit?
21. Is the relationship between true power, apparent power and reactive power the same in a parallel circuit as in a series circuit?

If a circuit contains both inductive and capacitive reactance, the resultant reactance can be determined by using the appropriate equations before using Equations 5a and 5b. That is, $X = X_L - X_C$ if X_L is greater than X_C or $X = X_C - X_L$ if X_C is greater than X_L . If $X_L = X_C$, the circuit acts purely resistive, and the true power is equal to the apparent power.

POWER FACTOR

A useful relationship in dealing with power in ac circuits is the ratio between true power and apparent power. This ratio is called the **POWER FACTOR (pf)** of a circuit and is obtained by dividing the true power by the apparent power:

$$\left(pf = \frac{P_{\text{true}}}{P_{\text{apparent}}} \right) \quad (7)$$

Since the true power is equal to $I_R^2 R$ and the apparent power is equal to $I_T^2 Z$, Equation 7 can be written as:

$$pf = \frac{I_R^2 R}{I_T^2 Z} \quad (7a)$$

for either a series or parallel circuit.

In a series circuit I_R and I_T are equal, and $\frac{I_R^2}{I_T^2}$ is equal to 1.

Thus:

$$\left(pf = \frac{R}{Z} \text{ (series circuit).} \right) \quad (8)$$

Since the true power is equal to $\frac{E_R^2}{R}$ and the apparent power is equal to $\frac{E_S^2}{Z}$,

Equation 7 can also be written as:

$$\begin{aligned} pf &= \frac{\frac{E_R^2}{R}}{\frac{E_S^2}{Z}} \\ &= \frac{E_R^2 Z}{E_S^2 R} \end{aligned} \quad (7b)$$

In a parallel circuit, E_R and E_S are equal, and $\frac{E_R^2}{E_S^2}$ is equal to 1. Thus:

$$\left(pf = \frac{E_R^2 Z}{E_S^2 R} = \frac{Z}{R} \text{ (parallel circuit).} \right) \quad (9)$$

Rearranging Equation 7, we find that, FOR A CIRCUIT CONTAINING BOTH RESISTANCE AND REACTANCE, MULTIPLYING THE EFFECTIVE VOLTAGE TIMES THE EFFECTIVE CURRENT (apparent power) BY THE POWER FACTOR GIVES THE TRUE POWER dissipated in a circuit. This can be written using Equation 6:

$$\left(P_{\text{true}} = pf \times P_{\text{apparent}} \right) \\ = pf \times E_S I_T. \quad (10)$$

Thus, if the power factor of a circuit is known, the true power can be found by measuring the input voltage and current.

Also, dividing both sides of Equation 10 by the power factor (pf) gives:

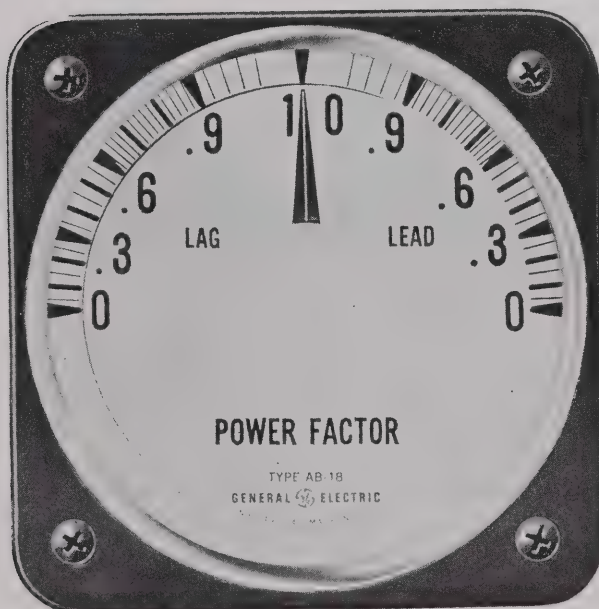
$$P_{\text{apparent}} = \frac{P_{\text{true}}}{pf} \quad (11)$$

Thus, if the power and the true power of a circuit are known, the apparent power can easily be found by dividing the true power by the power factor.

Referring to Equation 7, notice that the power factor of a circuit can never be greater than 1 since the true power can never be greater than the apparent power. In a purely resistive circuit there is no reactive power, and the apparent power is equal to the true power. However, IF THE CIRCUIT CONTAINS REACTANCE AND RESISTANCE, THE APPARENT POWER IS GREATER THAN THE TRUE POWER, giving a power factor of less than 1. In a purely reactive circuit, the true power is zero and the power factor is zero. The power factor is often multiplied by 100 to express it as a percentage. For example, a power factor of .5 could be expressed as 50%.

It is often desirable to maintain the power factor of a circuit as close to 1 as possible. The power factor indicates to what extent a circuit is reactive. The lower the power factor, the more reactive the circuit. A circuit with a low power factor must carry more current than that necessary to do the same amount of useful work in a circuit with a power factor of 1.

Alternators and transformers, for example, are rated in volt-amperes according to the current-carrying capacity of the windings and the dielectric strength of the insulation. The wattage available at the output, however, depends on the power factor. Some motors have lagging power factors (current lags voltage). The reactive current heats the windings of these motors without doing any useful work. In this case, the power factor is often increased by connecting capacitors across the motor windings. Such capacitors are called power-factor correctors.



The power factor meter shown above indicates both leading and lagging power factors. A leading power factor indicates a capacitive circuit and a lagging power factor indicates an inductive circuit.

Courtesy General Electric Co.

SUMMARY

The instantaneous power in a circuit is equal to the product of the instantaneous voltage and current. A positive instantaneous power indicates that power is being absorbed from the source. A negative instantaneous power indicates that power is being returned to the source. In a purely resistive ac circuit, the instantaneous power is always positive which indicates that all the power absorbed from the source by a resistance is dissipated in the form of heat. In a purely reactive circuit, the positive portions of the power curve equal the negative portions. This indicates that all the power absorbed from the source by a reactance is returned to the source later in the cycle.

In a purely resistive circuit, the product of effective voltage and effective current is the average or true power, and is one-half of the peak instantaneous power. True power is measured in watts. In a circuit containing reactance as well as resistance, the product of effective voltage and effective current is the apparent power measured in voltamperes. Apparent power is the vector sum of true power and reactive power. Reactive power is not dissipated as true power but is alternately absorbed from and returned to the source.

The ratio between true power and apparent power is called the power factor. Power factors range from 0 to 1. The lower the power factor, the more reactive the circuit is. Low power factors are usually undesirable, as a low power factor indicates that the circuit is largely reactive. Power companies usually charge only for dissipated or true power and not for reactive power. Therefore, they may require that a factory correct the power factor to near 1. If the load is inductive, this can be done by connecting large capacitors across the ac line.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

POWER EQUATIONS

POWER FACTOR

22. An ammeter on the control panel of an industrial control circuit indicates that the current in the circuit is 2 amperes. Measuring the resistance of the circuit with an ohmmeter gives a value of 30 ohms. What is the power dissipated by the unit?
23. A 220 volt ac motor draws 50 amperes from the ac power line. What is the apparent power?
24. What name is given to the ratio between true power and apparent power?
25. An electric motor draws 50 amperes from a 220 volt power line, but a wattmeter in the line indicates a true power of 9350 watts. What is the apparent power, and what is the power factor?
26. What are the formulas for determining the power factors of series and parallel circuits when the resistance and impedance are given?
27. The secondary circuit of a transformer has a power factor of .8. If the secondary voltage is 6 volts and the current is 20 amperes, what is the apparent power, and what is the true power in the secondary?

28. Electric lamp circuits commonly operate at a power factor of about .95. If an incandescent lamp dissipates 100 watts at a power factor of .95, what is the apparent power?
29. The power factor of a circuit can never be greater than 1. True or False?
30. The power factor of a purely resistive circuit is (a) 1, (b) 0, (c) .5.
31. The power factor of a purely reactive circuit is (a) 1, (b) 0, (c) 2.
32. Why do electric power companies require factories to correct the power factors of their equipment to near 1?
33. In a large machine shop containing many electric motors, transformers, and other inductive equipment, the line currents lag the line voltages. This results in power factors much smaller than 1, indicating that the power lines must carry larger currents than necessary. How can this undesirable condition be corrected?

IMPORTANT DEFINITIONS

APPARENT POWER (P_{apparent}) — The product of effective voltage and effective current. It must be multiplied by the circuit power factor to obtain the true power of the circuit.

AVERAGE POWER — See TRUE POWER.

POWER FACTOR (pf) — The ratio of the true power to the apparent power in an ac circuit. The factor by which the apparent power must be multiplied to obtain the true power.

REACTIVE POWER (P_{reactive}) — That power which, due to the reactance of the circuit, is stored during one part of a cycle and returned to the source during another part of the cycle.

TRUE POWER (P_{true}) — The power dissipated or consumed in an ac circuit in producing heat or doing useful work. True power is equal to the product of effective voltage and effective current (apparent power) times the power factor. True power is also called AVERAGE POWER.

VOLTAMPERES (VA) — The unit of apparent power.

VOLTAMPERE-REACTIVE (var) — The unit of reactive power.

WATTS (W) — The unit of true or average power.

ESSENTIAL SYMBOLS AND EQUATIONS

e	Instantaneous voltage (volts)
E_{peak}	The peak voltage of a sinewave (volts)
E_R	The effective voltage across a resistance (volts)
E_S	The effective source voltage of a circuit (volts)
E_X	The effective voltage across a reactance (volts)
i	Instantaneous current (amperes)
I_{peak}	The peak current of a sinewave (amperes)
I_R	The effective current through a resistance (amperes)
I_T	The total effective current in a circuit (amperes)
I_X	The effective current through a reactance (amperes)
p	Instantaneous power (watts)
P_{apparent}	Apparent power (voltamperes)
P_{ave}	Average power (watts)
P_{peak}	Peak power (watts)
P_{reactive}	Reactive power (reactive voltamperes)
P_{true}	True power (watts)
pf	Power factor
R	Resistance (ohms)
X	Reactance
Z	Impedance (ohms)
θ	Theta (degrees)

$$p = ei \quad (1)$$

$$P_{\text{peak}} = E_{\text{peak}} I_{\text{peak}} \quad (2)$$

ESSENTIAL SYMBOLS AND EQUATIONS (Continued)

$$P_{ave} = \frac{E_{peak} I_{peak}}{2} = \left(\frac{E_{peak}}{1.414} \right) \left(\frac{I_{peak}}{1.414} \right) \quad (3)$$

$$P_{ave} = E_{RMS} \times I_{RMS} \quad (3a)$$

$$P_{peak} = 2P_{ave} \quad (3b)$$

$$P_{true} = E_R I_R \quad (4)$$

$$P_{true} = I_R^2 R \quad (4a)$$

$$P_{true} = \frac{E_R^2}{R} \quad (4b)$$

$$P_{true} = P_{ave} \quad (4c)$$

$$P_{reactive} = E_X I_X \quad (5)$$

$$P_{reactive} = I_X^2 X \quad (5a)$$

$$P_{reactive} = \frac{E_X^2}{X} \quad (5b)$$

$$P_{apparent} = E_S I_T \quad (6)$$

$$P_{apparent} = I_T^2 Z \quad (6a)$$

$$P_{apparent} = \frac{E_S^2}{Z} \quad (6b)$$

$$pf = \frac{P_{true}}{P_{apparent}} \quad (7)$$

$$pf = \frac{I_R^2 R}{I_T^2 Z} \quad (7a)$$

$$pf = \frac{E_R^2 Z}{E_S^2 R} \quad (7b)$$

$$pf = \frac{R}{Z} \text{ (series circuit)} \quad (8)$$

**ESSENTIAL SYMBOLS AND EQUATIONS
(Continued)**

$$\text{pf} = \frac{E_R^2 Z}{E_s^2 R} = \frac{Z}{R} \text{ (parallel circuit)} \quad (9)$$

$$\begin{aligned} P_{\text{true}} &= \text{pf} \times P_{\text{apparent}} \\ &= \text{pf} \times E_s I_T \end{aligned} \quad (10)$$

$$P_{\text{apparent}} = \frac{P_{\text{true}}}{\text{pf}} \quad (11)$$

PRACTICE EXERCISE SOLUTIONS

1. The rate at which the device produces or uses electric energy.
2. (a) is in phase with the current. — The voltage lags the current in a capacitive circuit and leads the current in an inductive circuit.
3. (a) $p = ei$. — In this equation, the small letter symbols represent instantaneous values. Notice how this equation compares to the equation for power in a dc circuit ($P = EI$), where the capital letter symbols represent dc values.
4. True — In an ac circuit containing only resistance, the instantaneous power is always positive. This means that the toaster dissipates power in the form of heat during all portions of the cycle.
5. (b) average power. — Unless otherwise stated, the term “power” in an ac circuit refers to average power. In a purely resistive circuit, average power is equal to $1/2$ of the peak power.
6. $P_{ave} = 60$ watts, $P_{peak} = 120$ watts. — The average power is found using Equation 3a:

$$P_{ave} = E_{RMS} \times I_{RMS} = 120 \times .5 = 60 \text{ watts.}$$

Since the P_{ave} is $1/2$ of the P_{peak} , P_{peak} is equal to $2P_{ave}$. Thus, the peak power is:

$$P_{peak} = 2P_{ave} = 2 \times 60 = 120 \text{ watts.}$$
7. 20 watts — Since average power is one-half of the peak power, peak power is twice average power:

$$P_{peak} = 2P_{ave} = 2 \times 10 = 20 \text{ watts.}$$
8. True — An inductance absorbs power from the source as it builds up a magnetic field, and returns this power to the source when the field collapses.
9. False — All of the power absorbed from the source during one portion of the cycle is returned to the source during the next portion of the cycle.

PRACTICE EXERCISE SOLUTIONS (Continued)

10. Yes — With an inductive load, some of the power is returned to the source. In fact, in a pure inductance all of the power absorbed from the source is later returned to the source, resulting in an average power of zero. However, the inductance still requires current to build up the magnetic field. Thus, a factory with highly inductive loads may require a much larger current than that indicated by a wattmeter which indicates accumulated average power.
11. (a) zero. — The average power in a purely CAPACITIVE circuit is equal to one-half the peak power.
12. (a) watts. — True power is equal to average power.
13. (a) voltamperes. — The unit voltampere is used to distinguish apparent power from true power.
14. True — Since no power is returned to the source in a purely resistive circuit, the product of effective voltage and effective current equals both the apparent power and the true power.
15. No — In an ac circuit containing both inductance and resistance, the product of effective voltage and effective current is equal to the apparent power. In an ac circuit containing only resistance, the product of effective voltage and effective current is equal to the true power.
16. The var. — The term var stands for voltampere-reactive.
17. (b) reactive power. — There is no true power in a purely reactive circuit. Power is stored in the reactance during part of the cycle and returned to the source during the next part of the cycle.
18. The apparent power is the vector sum of true power and of reactive power.
19. (a) apparent power. — The apparent power is the vector sum of the true power and the reactive power.
20. The true power. — All of the reactive power is returned to the source.

PRACTICE EXERCISE SOLUTIONS (Continued)

21. Yes — In both series and parallel circuits, apparent power is the vector sum of true power and reactive power.

22. 120 watts. — Using Equation 4a:

$$\begin{aligned} P_{\text{true}} &= I_R^2 R \\ &= (2)^2(30) \\ &= 120 \text{ watts.} \end{aligned}$$

23. 11,000 voltamperes. — Using Equation 6:

$$\begin{aligned} P_{\text{apparent}} &= E_S I_T \\ &= 220 \times 50 \\ &= 11,000 \text{ voltamperes.} \end{aligned}$$

24. Power factor. — In the form of an equation:

$$\text{pf} = \frac{P_{\text{true}}}{P_{\text{apparent}}}$$

25. 11,000 voltamperes at a power factor of .85. — Using Equation 6:

$$\begin{aligned} P_{\text{apparent}} &= E_S I_T \\ &= 220 \times 50 \\ &= 11,000 \text{ voltamperes.} \end{aligned}$$

Using Equation 7:

$$\begin{aligned} \text{pf} &= \frac{P_{\text{true}}}{P_{\text{apparent}}} \\ &= \frac{9350}{11,000} \\ &= .85 \end{aligned}$$

26. For a series circuit, $\text{pf} = R/Z$. For a parallel circuit, $\text{pf} = Z/R$.

27. 120 voltamperes and 96 watts. — Using Equation 6:

$$\begin{aligned} P_{\text{apparent}} &= E_S I_T \\ &= 6 \times 20 \\ &= 120 \text{ voltamperes.} \end{aligned}$$

PRACTICE EXERCISE SOLUTIONS (Continued)

Using Equation 10:

$$\begin{aligned}
 P_{\text{true}} &= \text{pf} \times P_{\text{apparent}} \\
 &= .8 \times 120 \\
 &= 96 \text{ watts.}
 \end{aligned}$$

28. 105 voltamperes (approx.). — Using Equation 11:

$$\begin{aligned}
 P_{\text{apparent}} &= \frac{P_{\text{true}}}{\text{pf}} \\
 &= \frac{100}{.95} \\
 &= 105 \text{ voltamperes (approx.)}
 \end{aligned}$$

When the voltage is known, the circuit current can be determined from the apparent power by using the relation $I_T = \text{apparent power}/E_s$. Note that this will give a higher current than required for the true power. Therefore, the circuit conductors are required to carry a larger current than they would if the circuit were purely resistive and had a power factor of 1.

29. True — The true power can never be greater than the apparent power.
30. (a) 1. — The power factor of a purely resistive circuit is 1.
31. (b) 0. — The power factor in a purely reactive circuit is 0.
32. Because a power factor less than 1 indicates that a factory is drawing reactive current from the power company. The reactive current produces heat losses in the power company's lines. The factory owner pays for only the true power, so that any power dissipated in the line is a loss as far as the power company is concerned.
33. By installing large capacitors across the ac power lines. — The values of the capacitors are chosen so that their reactance will be equal to that of the inductances. Thus, the capacitances and inductances across the lines balance each other as in a resonant circuit. This leaves only the resistive portion of the line current and increases the power factors to 1.



ONE OF THE

BELL & HOWELL SCHOOLS

EXAMINATION
CHECK SHEET

1067A

1. A - THE AVERAGE POWER DISSIPATED BY A PURE RESISTANCE IS -- ONE HALF OF THE PEAK POWER.

The peak power is twice the average power which is the product of the RMS voltage and current.

2. A - AVERAGE POWER IN A PURELY RESISTIVE CIRCUIT IS EQUAL TO THE PRODUCT OF -- EFFECTIVE VOLTAGE AND EFFECTIVE CURRENT.

Average power is equal to the product of the RMS or effective voltage and current while peak power is equal to the product of peak voltage and current.

3. D - THE PRODUCT OF EFFECTIVE VOLTAGE AND EFFECTIVE CURRENT IN A CIRCUIT CONTAINING BOTH RESISTANCE AND REACTANCE IS THE -- APPARENT POWER.

The apparent power in a reactive circuit is equal to the vector sum of the true power and reactive power.

4. B - NO POWER IS DISSIPATED IN A -- PURELY REACTIVE CIRCUIT.

In a purely reactive circuit, power is absorbed by the reactance during part of the cycle and returned to the source during another part of the cycle.

5. D - THE POWER FACTOR OF A CIRCUIT IS EQUAL TO THE -- TRUE POWER DIVIDED BY THE APPARENT POWER.

The power factor of a purely resistive circuit is one. If the circuit contains reactance, the apparent power will be larger than the true power and the power factor will be less than one.

6. A - IN A CIRCUIT CONTAINING BOTH RESISTANCE AND REACTANCE, THE TRUE POWER IS EQUAL TO THE -- PRODUCT OF EFFECTIVE VOLTAGE AND EFFECTIVE CURRENT TIMES THE POWER FACTOR.

The true power is equal to the power factor times the apparent power (effective voltage times effective current).

7. A - WHAT IS THE POWER FACTOR IN A SERIES CIRCUIT WHERE THE IMPEDANCE IS 1000 OHMS AND THE RESISTANCE IS 850 OHMS? -- .85.

In a series circuit the power factor is equal to R/Z .

$$pf = \frac{R}{Z} = \frac{850}{1000} = .85$$

8. D - A RESISTOR THAT CARRIES 1.4 AMPERES OF EFFECTIVE CURRENT AND HAS 117 VOLTS EFFECTIVE ACROSS IT DISSIPATES A PEAK POWER OF -- 327.6 WATTS.

$$P_{\text{peak}} = 2P_{\text{ave}} = 2 \times 1.4 \times 117 = 327.6 \text{ watts.}$$

9. C - A RADIO TRANSMITTER WHICH DRAWS 15 AMPERES (EFFECTIVE) AT 220 VOLTS (EFFECTIVE) FROM THE AC POWER LINE HAS AN APPARENT POWER OF -- 3300 VOLTAMPERES.

Apparent power is equal to the product of the source voltage and source current.

$$P_{\text{apparent}} = E_S \times I_S = 220 \times 15 = 3300 \text{ voltamperes.}$$

10. C - A RADIO TRANSMITTER WHICH DRAWS 15 AMPERES (EFFECTIVE) AT 220 VOLTS (EFFECTIVE) FROM THE AC POWER LINE AND HAS A POWER FACTOR OF .85 DISSIPATES A TRUE POWER OF -- 2805 WATTS.

True power is equal to the apparent power times the power factor.

$$P_{\text{true}} = P_{\text{apparent}} \times pf = 15 \times 220 \times .85 = 2805 \text{ watts.}$$



EXPERIMENT 3

POWER IN AC CIRCUITS

PARTS NEEDED

- | | |
|--|---|
| 1 - Complete Design Console | 1 - 2.2 k Ω , 1/2 W, 5% Resistor |
| 1 - Multimeter with Test Leads and Spring Adapters | 3 - Modular Connectors |
| 1 - .1 μ F Disk Capacitor | - No. 22 Solid Hookup Wire |

OBJECTIVE

In this experiment you will examine the power distribution in an ac circuit including resistance and reactance. When reactance is present in an ac circuit, reactive power results. This causes the apparent power to be higher than the true power (the latter is the power actually dissipated by the circuit resistance).

PROCEDURE

1. Construct the circuit shown in Figure 3-1. Be sure to use the audio generator sinewave output. Leave the ADJUST VOLTAGE control set fully counterclockwise since the low voltage supply is not used in this experiment.
2. Turn on the design console and set the ADJUST FREQ. control to 0 (lowest audio generator frequency). Measure the audio generator ac output voltage and the ac voltage drop across R_1 , using the output function of your multimeter. Record the values below.

$$E_{R_1} = \underline{1.0} \text{ volts ac}$$

$$\text{Audio Generator Output, } E_S = \underline{3.6} \text{ volts ac}$$

3. Calculate the circuit current using Ohm's Law, and record it below.

$$I_T = \frac{E_{R_1}}{R_1} = \underline{.45} \text{ mA}$$

4. The apparent power for the circuit is found by taking the product of the source voltage (audio generator output) and the circuit current, as indicated below. Calculate and record the apparent power. Note that the unit for apparent power is the voltampere.

$$\text{Apparent Power (P}_A\text{)} = E_S \times I_T = \underline{1.62} \text{ m voltamperes}$$

The true power is the power dissipated in the circuit resistance and can be calculated as shown below. Calculate and record the true power.

$$\text{True Power (P}_T\text{)} = I_T^2 \times R_1 = \underline{.45} \text{ m watts}$$

$$.45 \times .45 \times 10^{-3} = .2025$$

Power in AC Circuits

Since the circuit contains a reactive element, C_1 , the apparent power will be greater than the true power.

5. The ratio of the true power to the apparent power is the power factor (pf). Calculate the power factor as shown below.

$$pf = \frac{P_T}{P_A} = \frac{.45 \text{ m}}{1.62 \text{ m}} = .28$$

In a circuit with both reactance and resistance, the power factor will always be less than 1 since the true power is always less than the apparent power.

6. The reactive power (P_X) can be determined from the true and apparent power by employing the power triangle formula:

$$P_A^2 = P_T^2 + P_X^2 \text{ or } P_X = \sqrt{P_A^2 - P_T^2} = \sqrt{1.62^2 - (.45)^2}$$

Calculate the reactive power and record below. Note that the unit for reactive power is VARS (voltamperes reactive).

$$\text{Reactive Power } (P_X) = 1.55 \text{ m vars}$$

You will note that the algebraic sum of the true and reactive powers is not equal to the apparent power. The apparent power is the vector sum of the true and of the reactive power.

7. If the frequency is varied in an ac circuit, the power distribution will change. Increasing frequency in an RC circuit will increase the true power and bring the power factor closer to 1.

Set the audio generator ADJUST FREQ. control to 10 (highest audio generator frequency). Measure the voltage drop across R_1 and the audio generator output, E_S , recording the values below.

$$E_{R_1} = 1.5 \text{ volts ac}$$

$$\text{Audio Generator Output, } E_S = 3.6 \text{ volts ac}$$

Calculate the circuit current and record it below.

$$I_T = \frac{E_{R_1}}{R_1} = \frac{1.5}{22 \text{ k}} = .68 \text{ mA}$$

8. Calculate the apparent power, true power, reactive power and power factor, recording the values below.

$$\text{Apparent Power } (P_A) = E_S \times I_T = 2.45 \text{ m voltamperes}$$

$$\text{True Power } (P_T) = I_T^2 \times R_1 = 1.02 \text{ watts}$$

Power in AC Circuits

$$\text{Reactive Power (P}_X\text{)} = \sqrt{P_A^2 - P_T^2} = \underline{2.28 \text{ m vars}}$$

$$\text{pf} = \frac{P_T}{P_A} = \frac{1.02}{2.45} = \underline{.42}$$

Your calculated values for true power and power factor should be higher than those values obtained earlier at a lower operating frequency.

CONCLUSION

In an ac circuit containing uncancelled reactance, the actual power dissipated in the circuit (the true power) is less than the apparent power. The product of the source voltage and circuit current is equal to only the apparent power. The reactive power accounts for the difference between the true power and the apparent power with the vector sum of the true and the reactive powers equaling the apparent power.

When the value of the reactance in a series circuit is low, the true power will be close to the apparent power (the power factor will be close to 1). On the other hand, when the reactance is high compared to the resistance, the true power will be much lower than the apparent power, resulting in a power factor much less than 1.

NOTES

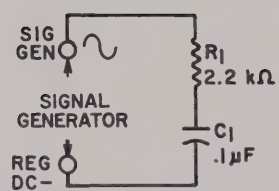


FIGURE 3-1

NOTES

1. B - WHAT IS THE FORMULA USED TO CALCULATE APPARENT POWER? -- $P = E_S \times I_T$.
The apparent power is equal to the product of the source voltage and of the circuit current.

2. D - SUPPOSE THAT THE TRUE POWER IN AN AC CIRCUIT IS 3 WATTS AND THAT THE POWER FACTOR IS 0.8. WHAT IS THE APPARENT POWER? -- 3.75 VOLTAMPERES.
The apparent power is calculated by rearranging the power factor formula:

$$pf = \frac{P_T}{P_A}$$

$$P_A = \frac{P_T}{pf} = \frac{3 \text{ watts}}{.8} = 3.75 \text{ voltamperes.}$$

1. Note: The correct unit for apparent power is voltamperes, not watts.

3. A - IN A SERIES AC CIRCUIT CONTAINING R AND C, IF THE SOURCE FREQUENCY DECREASES, THE -- POWER FACTOR BECOMES CLOSER TO ZERO.
A decrease in frequency causes an increase in X_C , thus increasing the reactive power and making the power factor even smaller.

4. D - WHAT IS THE FORMULA FOR DETERMINING THE REACTIVE POWER? -- $P_X = \sqrt{P_A^2 - P_T^2}$.
The reactive power formula is a rearrangement of the basic power triangle formula:

$$P_A^2 = P_T^2 + P_X^2$$

$$P_X^2 = P_A^2 - P_T^2 \text{ or } P_X = \sqrt{P_A^2 - P_T^2}$$

5. B - HOW CAN THE POWER FACTOR OF THE CIRCUIT SHOWN IN FIGURE 3-1 BE MADE EQUAL TO 1?
-- ADD JUST ENOUGH INDUCTANCE TO MAKE THE CIRCUIT PURELY RESISTIVE.
When a circuit is resonant, it appears purely resistive; and the power factor will be equal to 1.

NETWORKS

1070





Television receivers employ a number of filter circuits. A low-pass filter in the power supply provides smooth dc to the various circuits. High-and low-pass filters are used to separate the pulses which synchronize the picture.

Courtesy Sony Corporation of America

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Lost

*Between Sunrise and Sunset, two precious hours
Set with Golden Opportunities,
No reward offered—they are gone forever.*

NETWORKS

Our senses react far too slowly to detect many electronic actions. To our eyes and ears, many things which seem to occur instantaneously actually require definite and measurable periods of time. You can carry on a conversation between New York City and San Francisco by long distance telephone without any noticeable pauses. Yet, it requires an appreciable part of a second for the electric energy form of your voice to travel the 3,000 miles between the two cities.

The highest known velocity, that of light and electromagnetic radiation, is approximately 186,000 miles per second. This velocity can also be stated as .00000537 seconds per mile.

When measuring small time quantities, it is customary to divide a second into one million parts, with each of these parts called a **MICROSECOND** (μ sec). Thus, multiplying by one million, .00000537 second is equal to 5.37 microseconds. At this rate, it requires $5.37 \times 3,000$, or 16,110 microseconds for electric energy to travel from New York to San Francisco. This may seem like a long time, but it is equal only to 0.016 second, an interval too short to be noticed as a conversational pause.

When an electric lamp is switched on, it appears to light instantly. Actually, in terms of microseconds, an appreciable amount of time is required for the lamp to reach full brilliance. The explanations of the early lessons assumed that the action of electric energy was instantaneous. However, in subsequent lessons it was shown that inductance delays a change of current, and capacitance delays a change of voltage.

Every circuit includes the three properties of resistance, inductance and capacitance. Because of the speed of many electric and electronic actions, the slight delays caused by inductance and capacitance become important.

This lesson explains the effects of **RL CIRCUITS** and **RC CIRCUITS** on ac and dc sources, and shows how it is possible to selectively filter or separate currents or voltages of different frequencies.

The property of inductance causes the current to lag the voltage in a sinewave ac circuit. In such circuits, the lag, or phase angle, depends upon the relationship between reactance and resistance. The inductive reactance changes

with frequency, as $X_L = 2\pi fL$. In ac circuits, the phase angle between the current and voltage depends upon the frequency of the voltage as well as the resistance and inductance. In dc circuits, the time lag depends only upon the inductance and resistance of the circuit.

RL CIRCUITS

If a dc voltage is applied to a circuit that contains only resistance, the current is determined by Ohm's Law: $I = E/R$. The current attains this value the instant the circuit switch is closed, and it is as continuous and unvarying as the source voltage. However, if the circuit contains inductance as well as resistance, the current is held back by the inductor's counter emf, and does not rise to the maximum value immediately. Figure 1A shows the increase of current with time when the circuit of Figure 1B is connected to a dc source. The shape of this current change follows an EXPONENTIAL CURVE. The current increases rapidly at first and then gradually tapers off to its maximum value. (We will assume an ideal dc source. The impedance of such a source is zero.)

Observation of Figure 1A shows that for each equal consecutive vertical line interval of time, the current increase is less than during the previous interval. In the first time interval, the current rises to 63.2% of its final value; in the second interval the current rises to 86.5% of its final value; in the third interval the current rises to 95%; in the fourth interval it reaches about 98.2%, and at the end of the fifth interval the current is about 99.3% of maximum, which is so near 100% that for all practical purposes the current is considered to be at its maximum.

Now assume that the dc output of the supply dropped to zero. With zero impedance, the supply looks like a short from points X to Y in Figure 1B. Switch S is still closed. The current in the inductor does not fall immediately to zero, but, starting from maximum, follows a curve shape like that shown in Figure 1C. Notice that this curve is the opposite, or inverse, of the Figure 1A curve. The current falls rapidly at first, then tapers off toward zero. In the first interval, it falls 63.2% from its maximum. This is $100 - 63.2$, or 36.8% above zero, as read to the left of the 63.2% point on the percent ordinate—slightly below the 40% mark.

Like the rise to maximum, the decrease of current at the end of the second interval is 86.5% from the maximum. This process continues until the end of the fifth interval, when, for all practical purposes, the current is zero.

For each successive interval, the increase (or decrease) of current is 63.2% of its remaining value. For example, at the end of the first interval in Figure 1A, the current has increased to 63.2% of the maximum (100%). At the

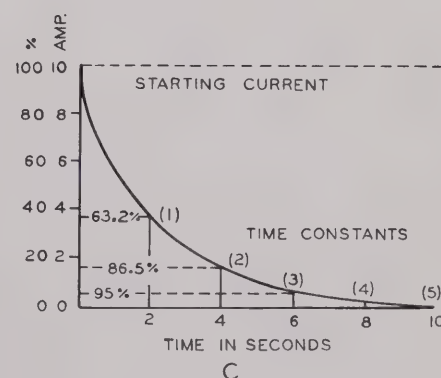
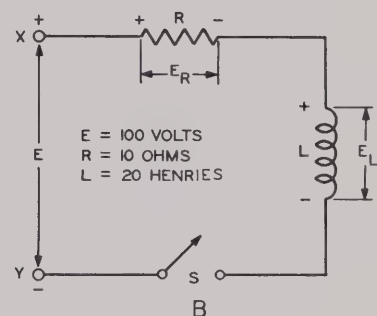
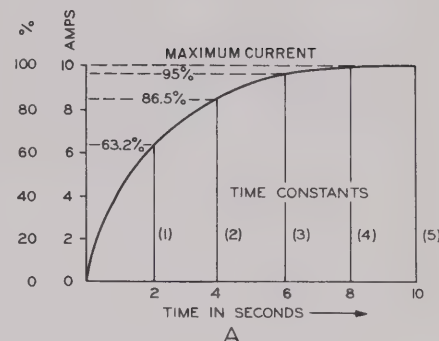


Figure 1

end of the second interval, the current has increased to 63.2% of the remaining 36.8%, for a total of 86.5% of maximum. At the end of the third period, the current has increased to 63.2% of the remaining 13.5%, or a total of 95%.

This recurring 63.2% of the rise or fall of current in a fixed interval of time is called the **TIME CONSTANT** of the circuit. The time interval in which the current rises to 63.2% of its maximum is the first time constant. At the end of three time constants, the current is at 95% of its maximum.

INDUCTOR CURRENT CHANGE			
Column 1	Column 2	Column 3	Column 4
At the End of Time Constant	Increase of Current (% of remaining change)	Total Current (% of maximum)	Remaining Current change (% of maximum)
1	63.2% of 100 = 63.2	0 + 63.2 = 63.2	100 - 63.2 = 36.8
2	63.2% of 36.8 = 23.3	63.2 + 23.3 = 86.5	100 - 86.5 = 13.5
3	63.2% of 13.5 = 8.5	86.5 + 8.5 = 95.0	100 - 95 = 5.0
4	63.2% of 5.0 = 3.2	95.0 + 3.2 = 98.2	100 - 98.2 = 1.8
5	63.2% of 1.8 = 1.1	98.2 + 1.1 = 99.3	100 - 99.3 = .7
6	63.2% of .7 = .44	99.3 + .44 = 99.74	100 - 99.74 = .26
7	63.2% of .26 = .16	99.74 + .16 = 99.9	100 - 99.9 = .1

Figure 2

The relationships between the percent of maximum current and time constants are shown in the chart of Figure 2. Although the chart shows the current change for seven time constants, only five are shown in the graphs of Figure 1. In practice, five time constants are considered to constitute a full change (or discharge).

In an RL circuit the time required to reach maximum charge increases with increasing values of inductance. This condition is understandable, as a greater L has a greater counter emf, causing a slower current rise. Conversely, if the resistance is greater, a shorter time is required for the current to reach its maximum, since the smaller counter emf permits greater current.

L/R Time Constant

The time constant of an RL circuit, in seconds, is equal to the circuit inductance divided by the circuit resistance:

$$T = L/R \quad (1)$$

where: T is the time constant in seconds,

L is the inductance in henries, and

R is the resistance in ohms.

Using Figure 1B as an example, E is 100 volts (dc), R is 10 ohms, and L is 20 henries. The final or maximum current in the circuit is: $I = E/R = 100/10 = 10$ amperes. The time constant, $L/R = 20/10 = 2$ seconds, means that 2 seconds are required for the current to reach 63.2% of 10, or 6.32 amperes. In Figure 1A, the point where the charge curve reaches the vertical line representing 1 time constant equals a little more than 6 amperes, as shown on the 0 to 10 ampere current scale at the left side of the graph.

The current at the end of the 2nd and 3rd time constants is 8.65 and 9.5 amperes, respectively. The graph is a little too small to read the 4th and 5th time constants, but these values can be read in the chart of Figure 2. At the end of the 4th time constant the current is 9.82 amperes, and at the end of the 5th time constant the current is 9.93 amperes.

When the dc supply voltage of Figure 1B is opened, the current decreases, as shown by the curve of Figure 1C. At the end of the 1st time constant, the current decreases 63.2% from its maximum, or falls $.632 \times 10$, or 6.32 amperes. The current in the circuit at this instant is $10 - 6.32$, or 3.68 amperes. With 10 amperes as the maximum current, the percentages shown in column four of the chart of Figure 2, multiplied by 10 amperes, give the corresponding current in the circuit at the ends of up to 7 time constants.

Let's see what happens when the inductance is changed. Assume that the inductance, L, is now 40 henries and R is still 10 ohms. The time constant is $T = L/R = 40/10 = 4$ seconds. Now, 4 seconds is required for the current to reach 63.2% of maximum after the switch is closed. A total of 8 seconds is required for the current to reach 86.5% of 10 amperes, or 8.65 amperes.

Now, assume that the circuit resistance is increased. Let $R = 50$ ohms, $E = 100$ volts, and $L = 20$ henries. $T = L/R = 20/50 = .4$ second. Because the resistance is large in comparison to the inductance, the back emf is less effective, and the current reaches its maximum more quickly than for our original example. However, notice that the maximum current, $I = 100/50 = 2$ amperes. This means that the current at the end of each successive time constant is less.

Going back to Figure 1B, starting at the instant the dc voltage is applied through closed switch S, the current increases from zero to its final value as shown by the curve of Figure 1A. This current change results in an induced voltage, E_L , which has a polarity opposite to that of E , as indicated by the plus and minus signs. As E and E_L are in SERIES OPPOSITION, the effective, or net voltage, is equal to $E - E_L$, or E_n . Simultaneously, the current is opposed by the circuit resistance so that at any instant the current has a value equal to E_n/R .

An instant after the voltage is applied, the rate of current change is rapid, and therefore the induced voltage, E_L , is large, the net voltage, E_n , is small, and the circuit current is low. However, as the current approaches maximum, its rate of change is slow, the induced voltage decreases, the net voltage increases, and the circuit current is correspondingly larger. Current through a resistance causes a voltage drop, and the voltage drop, E_R , of Figure 1B is in step with the change of current. In effect, a voltage curve, E_R , has the same shape as the current curve of Figure 1A.

Because inductance is frequently measured in microhenries, the necessity of converting the inductance to henries can be avoided by thinking of the time constant in terms of microseconds. That is, the known values in microhenries and ohms may be substituted directly into the equation:

$$T = L/R$$

if T = time in microseconds,

L = inductance in microhenries, and

R = resistance in ohms.

Then, if $R = 10$ ohms and $L = 100$ microhenries, the time constant is:

$$\begin{aligned} T &= L/R \\ &= 100/10 \\ &= 10 \text{ microseconds.} \end{aligned}$$

A "universal" time constant chart for RL and RC circuits is shown in Figure 3. Curve 1 has the same shape as the curve of Figure 1A, and curve 2 has the same shape as Figure 1C. The vertical scale is marked in percent of maximum voltage or current, and the horizontal scale is marked in time constants.

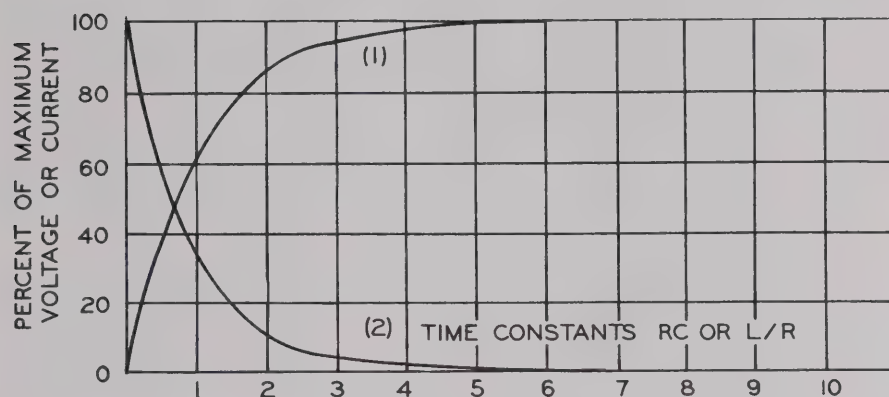
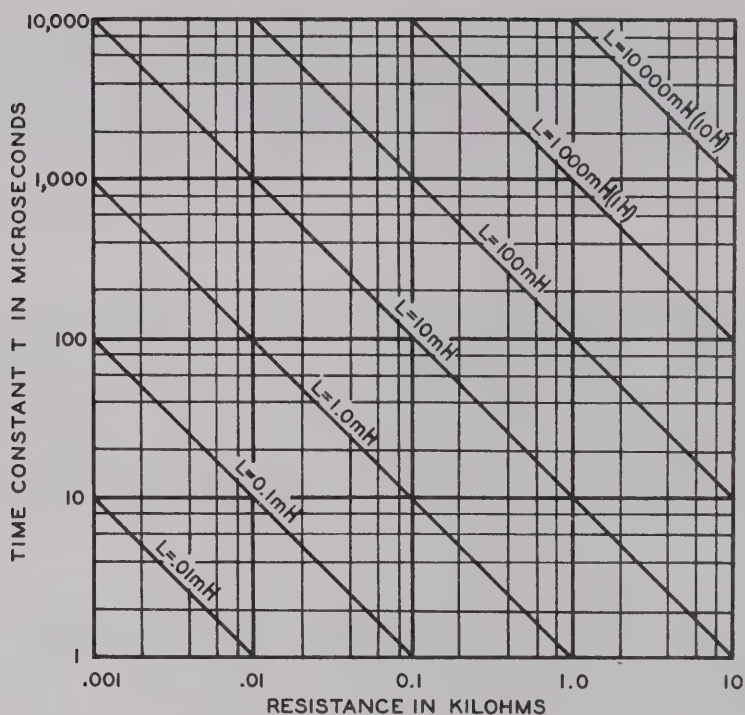


Figure 3

Let's see how the curves of Figure 3 can be used to determine some instantaneous voltages. In the circuit of Figure 1B, the maximum voltage drop is 100 volts. What is the instantaneous voltage across the resistor at the end of the 3rd time constant? Checking curve 1 of Figure 3, and reading to the left from the curve, at the 3rd time constant the approximate percentage is 95. Multiplying by the maximum voltage, 100, the voltage drop is 95 volts.

The induced voltage, E_L , follows the shape of the curve of Figure 1C. As the current change is large at the instant switch S of Figure 1B is closed, the counter emf is large, and it gradually decreases as the change of current becomes less; finally it reaches approximately zero at the end of five time constants. This maximum change of decreasing voltage takes place in five time constants, as does the maximum change of increasing voltage.

A simplified method of determining the relationship between time constants, resistance and inductance is given in the explanation for using the graph of Figure 4.



This graph shows time constants for various combinations of resistance and inductance. To read the graph, begin at a point along the bottom scale corresponding to the known resistance, follow the vertical line up to the diagonal line representing the known inductance. From this intersection, follow the horizontal line to the left to the indicated time constant.

Figure 4

Decay of Current in an RL Circuit

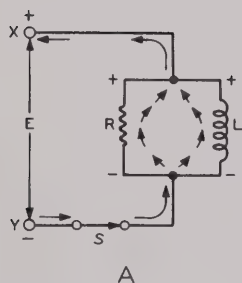


Figure 5

When an applied voltage is removed from an RL circuit, the coil current decreases or DECAYS gradually. The time required for the current to reach zero depends upon the time constant. In Figure 5A, a steady voltage, E , is applied to a resistor, R , and an inductor, L , which are connected in parallel across the voltage source. As indicated by the arrows, the current divides at the junction of R and L with part of the current carried by each component. For this discussion, we will assume that L is large, and also has appreciable dc resistance.

When the current in L reaches its final or steady value, it isn't affected by the inductance of the coil. In fact, the only opposition to current in this branch of the circuit is that offered by the resistance of the coil wire. Therefore, as long as the applied voltage, E , does not change, the circuit of Figure 5A is equivalent to a circuit containing two resistors in parallel. The same voltage is applied to both components, and the respective currents cause voltage drops across R and L having the polarities indicated by the plus and minus signs.

Figure 5B shows the conditions existing in the circuit for a short time after the applied voltage has been removed by opening switch S. As in any resistive circuit, the current produced by E is opposed by R and the coil resistance, and tends to drop to zero immediately. This rapid decrease of current in L induces a voltage, E_L , with the indicated polarity.

This induced voltage is opposite in polarity to that which opposed a current increase, and therefore, it tends to maintain electron flow in L in the same direction it had when the switch was closed. With S open, the only path for these electrons is provided by resistor R , as shown by the arrows. Thus, the voltage across R is equal to E_L at any instant and has the polarity indicated. Notice that the current in L now has the same direction as when switch S was closed, but current through R is now in the opposite direction to what it was when S was closed.

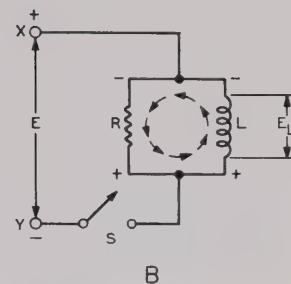


Figure 5

After the initial rapid decrease when the switch is opened, the current falls more slowly and the induced voltage decreases at a lower and lower rate, until both are reduced to zero. The voltage across resistor R —always proportional to the current and equal in magnitude to the induced voltage, E_L —varies in the same way, decreasing from an initial high value to zero. The rates at which the current and voltage decrease are determined by the time constant of the circuit. Curve 2 of Figure 3 represents the changes of E_L , E_R and the current in R and L , from the instant the switch is opened until the three quantities I , E_L and E_R have decreased to zero.

As indicated by the time constant equation, $T = L/R$, the greater the inductance in the circuit, the longer it takes for the current to decay to a given value or zero. In contrast, the higher the resistance, R , the less time it takes for the current to drop to zero. This may sound strange, but consider the extreme case in which R is removed entirely from the circuit so that there is infinite resistance in series with L when the switch is opened. The current must drop to zero instantly because no complete path exists for the electron flow. Conversely, suppose that, just before opening the switch, L is shorted with a wire to provide a current path having a total resistance of 1 ohm. If $L = .5$ henry and T is equal to $.5/1 = .5$ second, it will take five time constants ($5 \times .5$) or 2.5 seconds for the current to fall to zero.

RC CIRCUITS

The property of capacitance causes the current to lead the voltage in an ac circuit. In such circuits, the phase angle depends upon the relationship between the reactance and resistance. Capacitive reactance varies inversely

with frequency, as indicated in the expression $X_C = \frac{1}{2\pi fC}$. The phase angle

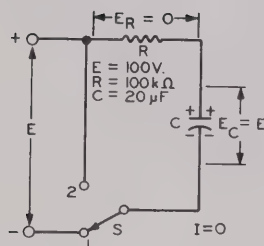


Figure 6

between the current and voltage in an ac capacitive circuit depends upon the voltage frequency, resistance and capacitance. In dc circuits, the time lead depends only upon the resistance and capacitance of the circuit.

The simple RC circuit shown in Figure 6 consists of a resistor, R , a capacitor, C , and a switch, S , connected in series across voltage source, E . When the switch is closed to position 1, the circuit is completed and electrons flow from the source negative terminal through switch S to the lower plate of capacitor C , and from the upper capacitor plate through resistor R to the positive terminal of the voltage source.

Because of the current-limiting effect of the resistor, the capacitor does not charge instantly. In fact, an appreciable time is required for the number of electrons necessary to charge the capacitor to flow through the resistor. The exact time required to complete the charge depends on both the capacitance and resistance of the circuit. The capacitance determines how many electrons are required for the full charge, and the resistance determines how rapidly these electrons can be supplied.



An oscilloscope provides a convenient means of observing the waveshaping effects of an RC or RL circuit.

Courtesy Tektronix Inc.

When dc is applied to an RC circuit, the rising circuit current reaches maximum almost instantly, as determined by $I = E/R$, and then gradually falls to zero as the voltage across the capacitor builds up. The curve of Figure 1C shows this action. Consider the vertical scale line at the left as representing the instantaneous rise of current to maximum. Then, as the capacitor begins to charge or build up a voltage, the charging current decreases gradually to zero. The current in an RC circuit decreases in exactly the same way as in an inductive circuit. In the first time interval, the current falls 63.2% from its maximum value, or to 36.8% of its initial value.

The fourth column of the chart of Figure 2 may be used to find the circuit current at the end of each of the equal time intervals. Curve 2 of Figure 3 is the same current change when the horizontal line of the graph represents RC time constants.

Since the same exponential curve relationship holds true for RC circuits as for RL circuits, the recurring 63.2% fall from maximum current in a fixed time interval is also the TIME CONSTANT of an RC circuit.

RC Time Constant

The time constant of an RC circuit is equal to the resistance multiplied by the capacitance:

$$(T = RC) \quad (2)$$

where: T = time constant in seconds,

R = resistance in ohms, and

C = capacitance in farads.

Using Figure 6 for an example calculation of RC time constant, R is 100,000 ohms or 1×10^5 ohms, and C is 20 microfarads or 20×10^{-6} farads. The time constant of this circuit is:

$$T = RC$$

$$= 1 \times 10^5 \times 20 \times 10^{-6}$$

$$= 20 \times 10^{-1}, \text{ or 2 seconds.}$$

With an applied dc voltage of 100 volts, the initial or maximum current is:

$$I = E/R$$

$$= \frac{1 \times 10^2}{1 \times 10^5}$$

$$= 1 \times 10^{-3}, \text{ or } 1 \text{ mA.}$$

Thus, a time duration of 2 seconds is required for the current to fall 63.2% from its maximum, or to 36.8% of 1 mA. At this point, the current in this example is $.368 \times .001 = .000368$ ampere, or .368 milliampere. Accordingly, at the end of the second time constant the current is 13.5% of 1 mA, or .135 milliampere. At the end of the five time constants the current is practically zero.

Of course, during this period of current fall, the capacitor is charging, and the voltage across the capacitor rises exactly as shown by curve 1 of Figure 3. The values at the end of each time constant are shown in column 2 of Figure 7. The corresponding voltage across the capacitor, expressed as a percentage of the applied voltage, is listed in the third column of Figure 7 for several time constant intervals. For all practical purposes, the full change takes place in five time constants. While the current falls to .368 milliampere in one time constant, the charge or capacitor voltage rises to 63.2% of the applied voltage. At this time, the capacitor voltage is $.632 \times 100$, or 63.2 volts. The change continues until the capacitor is fully charged.

CAPACITOR CHARGE CHART			
Column 1	Column 2	Column 3	Column 4
At the End of Time Constant	Increase in Capacitor Voltage (% of applied voltage)	Total Capacitor Voltage (% of applied voltage)	Effective Voltage (% of supply)
1	63.2% of 100 = 63.2	0 + 63.2 = 63.2	100 - 63.2 = 36.8
2	63.2% of 36.8 = 23.3	63.2 + 23.3 = 86.5	100 - 86.5 = 13.5
3	63.2% of 13.5 = 8.5	86.5 + 8.5 = 95.0	100 - 95.0 = 5.0
4	63.2% of 5.0 = 3.2	95 + 3.2 = 98.2	100 - 98.2 = 1.8
5	63.2% of 1.8 = 1.1	98.2 + 1.1 = 99.3	100 - 99.3 = .7
6	63.2% of .7 = .44	99.3 + .44 = 99.74	100 - 99.74 = .26
7	63.2% of .26 = .16	99.74 + .16 = 99.9	100 - 99.9 = .1

Figure 7

The following Practice Exercise questions cover the subjects which you have just studied. They are:

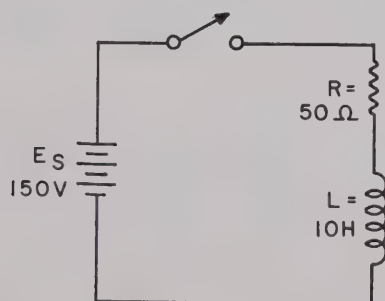
RL CIRCUITS

L/R TIME CONSTANT

DECAY OF CURRENT IN AN RL CIRCUIT

RC CIRCUITS

1. What is a microsecond?
2. What is the phase relationship between voltage and current in an inductive circuit?
3. During one time constant, what is the **CHANGE** of current in an RL circuit?
4. How many time constants are required for a full change of current in an RL circuit?
5. What is the total change in current at the end of 3 time constants in an RL circuit?
6. What is the formula for determining the time constant of an RL circuit?
7. In the following circuit, what is the maximum value of current, and how long will it take for the current to reach maximum after the switch is closed?



8. What happens to the time constant of an RL circuit when the value of R is increased?

9. Describe the action in Figure 5 when the switch is opened.
10. Decreasing the value of R in Figure 5 causes the induced voltage developed across the coil to decay faster. True or False?
11. What is the phase relationship between voltage and current in an RC circuit?
12. At the instant the switch is closed, what is the value of circuit current and the voltage drop across C in Figure 6?

Let's see if the basic rule of voltage drops in a series circuit holds true here. At the end of one RC time constant, the circuit current is 36.8% of 1 mA, or .000368 ampere. The capacitor voltage is 63.2% of 100 volts, or 63.2 volts. The sum of the voltage drops equals the applied voltage. The voltage drop across the resistor $E_R = IR = .000368 \times 100,000 = 36.8$ volts. Thus, the voltage across the capacitor $E_C + E_R = 63.2 + 36.8 = 100$ volts, which is the same as the applied voltage.

In practical circuits, knowledge of the voltage across the capacitor or its charged condition is of more value to the technician than the decrease of current in the RC circuit. The more capacitance in the circuit, the longer the time required to reach 63.2% of full charge. Also, the greater the resistance, the less current there is available to charge the capacitor, and the longer the time required to reach full charge.

Equation 2 does not contain a voltage term, as the source voltage makes no difference in the time constant. For components of appropriate ratings, regardless of the voltage impressed across the RC circuit, the capacitor will charge to 63.2% of the source voltage during the interval of the first time constant. This is assuming that the capacitor had zero charge at the start of the time constant interval. At any rate,

**DURING EACH SUCCESSIVE TIME CONSTANT
INTERVAL, THE CAPACITOR VOLTAGE WILL
CHANGE BY 63.2% OF THE TOTAL REMAINING
CHANGE THAT CAN OCCUR.**

To illustrate the use of the chart of Figure 7 and curve 1 of Figure 3, consider an RC circuit like that of Figure 6 in which $R = 25,000$ ohms, $C = .02 \mu\text{F}$, and $E_A = 500$ volts. What is the approximate voltage across the capacitor at the end of the second time constant, and how many microseconds are required for the capacitor to charge to the source voltage?

Reading from curve 1 of Figure 3, the 2nd time constant line cuts the curve at approximately 86%; or from column three of the chart of Figure 7, at exactly 86.5%. Thus, $.865 \times 500 = 432.5$ volts. Since the time constant of the circuit is:

$$T = RC$$

$$= 2.5 \times 10^4 \times .02 \times 10^{-6}$$

$$= .05 \times 10^{-2}, \text{ or } .0005 \text{ second, or } 500 \text{ microseconds, then for } 2$$

time constants the charging time required to reach 432.5 volts is 2×500 , or 1000 microseconds.

Capacitor Discharge through a Resistor

By definition, a time constant is the time required for a quantity to change by 63.2% of the maximum change that can occur. Nothing in the definition indicates whether the change is to a higher or lower value. The time constant applies to both charging and discharging capacitors.

In Figure 6, with the switch in position 1, the resistor, R , and capacitor, C , are connected in series across the voltage source, E , and the capacitor charges in the manner described. When the capacitor is fully charged, its voltage, E_C , is equal to the applied voltage, E . At this time, the resistor voltage, E_R , is equal to zero and the circuit current is zero.

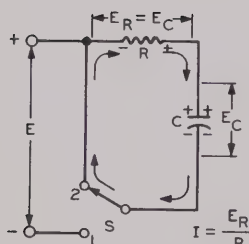


Figure 8

To start the discharge period, switch S is placed in position 2, as shown in Figure 8, thus disconnecting the voltage source, and connecting the resistor directly across the capacitor. Now the capacitor becomes the voltage source. The capacitor discharges by forcing electrons from its negative plate through the switch, S , and resistor, R , to its positive plate, as indicated by the arrows.

CAPACITOR DISCHARGE		
Column 1	Column 2	Column 3
At the End of Time Constant	Decrease of Capacitor Voltage (% of initial voltage)	Remaining Capacitor Voltage (% of maximum voltage)
1	63.2% of 100 = 63.2	100 - 63.2 = 36.8
2	63.2% of 36.8 = 23.3	36.8 - 23.3 = 13.5
3	63.2% of 13.5 = 8.5	13.5 - 8.5 = 5
4	63.2% of 5 = 3.2	5 - 3.2 = 1.8
5	63.2% of 1.8 = 1.1	1.8 - 1.1 = .7
6	63.2% of .7 = .44	.7 - .44 = .26
7	63.2% of .26 = .16	.26 - .16 = .1

Figure 9

As in the charging circuit, the time required for the discharge electrons to flow through the resistor is determined by the time constant of the circuit. Again, a 63.2% change occurs during each time constant, regardless of the initial value of voltage charge on the capacitor. For each succeeding interval, the voltage decreases by 63.2% of the remainder. Assuming 100% charge at the start, the capacitor discharge for seven time constant intervals is as listed in the chart of Figure 9.

A comparison of the last columns of the charts of Figures 7 and 9 shows that the effective voltage during charge, and the remaining capacitor voltage during discharge, are identical. Therefore, curve 2 of Figure 3 represents not only the circuit current and resistor voltage during charge, but also the capacitor voltage during discharge.

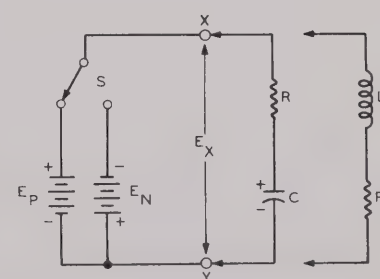
In the circuit of Figure 8, the capacitor is the voltage source. Therefore, the resistor and capacitor voltages are equal at all times during the discharge period. Curve 2 of Figure 3 represents the resistor voltage. Always proportional to the voltage causing it, the discharge current has a high initial value which then decreases at the same rate as the resistor voltage. Thus, curve 2 of Figure 3 also represents the discharge current of Figure 8.

As the capacitor discharges, its voltage, the resistor voltage and the circuit current decrease until, at the end of five time constant intervals, the capacitor is considered discharged, and $E_C = 0$, $E_R = 0$ and $I = 0$.

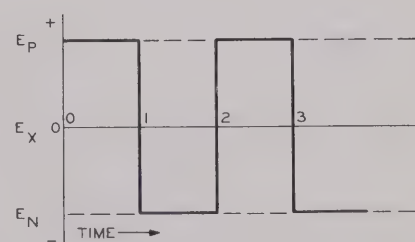
AC EFFECTS

In Figure 10A, a resistor and capacitor are connected in series with a source of voltage. The source consists of two batteries with a switch, S, arranged so that either battery may be connected to terminal X. When switch S is connected to battery E_P , terminal X is made positive with respect to terminal Y, and when switch S is connected to E_N , terminal X becomes negative with respect to terminal Y.

If the switch is alternately set to one position and then the other, and held at each for equal intervals of time, the voltage across points X and Y will be as shown by the rectangular curve of Figure 10B. To produce voltage E_X , switch S is set to the left and held there during the interval between 0 and 1 on the time axis of Figure 10B. Then, at time instant 1, the switch is thrown quickly to the right to connect the negative terminal of battery E_N to X. X is negative during the interval between time instants 1 and 2, after which S is returned to the positive terminal of battery E_P , making X



A

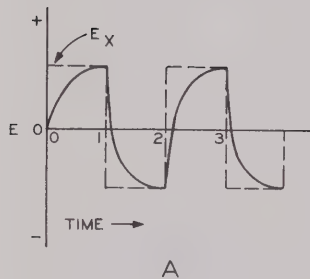


B

Figure 10

positive again. At time instant 3, switch S position is changed again, making X negative, and the process is continued for as long as a rectangular wave-form voltage is desired.

With the resistor, R, and capacitor, C, connected in series across terminals X and Y, when terminal X is positive, electron flow charges C to the polarity indicated in Figure 10A. During the intervals that terminal X is negative, the electrons flow in the opposite direction, and C becomes charged to the opposite polarity.



At the beginning of each interval, just after the applied voltage has changed polarity, the capacitor discharges completely before it can charge in the opposite direction. Then, during the remainder of the interval, the charge increases rapidly at first and then more slowly. This causes the capacitor voltage to have the form shown by the solid line curve in Figure 11A. The slope of the waveform depends upon the circuit RC time.

If C is completely discharged initially, the capacitor voltage is zero when switch S is first connected to E_P , and it then rises rapidly toward the positive voltage E_X , as indicated by the dashed line. After time instant 1, when switch S is connected to E_N , the capacitor voltage falls rapidly, passes through zero, and then increases toward the negative value of E_X . After ensuing time instants, this action is repeated in alternate directions to produce the voltage waveform shown by the solid line in Figure 11A.

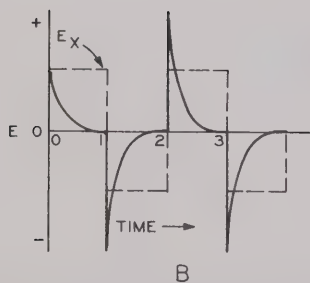


Figure 11

When the capacitor is charging or discharging rapidly, the circuit current is large, but decreases as the capacitor approaches a full charge. Since the voltage across resistor R depends on the circuit current, it has the form shown by the solid line curve in Figure 11B. The slope of the waveform depends upon the RC time. The applied voltage, E_X , is represented by the dashed line, and the first time the switch is closed to E_P , at time constant 0, the entire applied voltage appears across the terminals of the resistor. As the capacitor charges, the current decreases and the voltage across R is reduced proportionately, approaching zero as C nears full charge.

At time instant 1, the capacitor voltage is practically equal to E_P , and the resistor voltage has almost decreased to zero. Now switch S is connected to E_N , and the battery and capacitor voltages are series aiding to produce a very large circuit current. This produces a large negative voltage across R, equal to almost twice E_N . This voltage falls rapidly toward zero, and these narrow voltage pulses are produced across resistor R with alternate polarities as the switch is flipped back and forth.

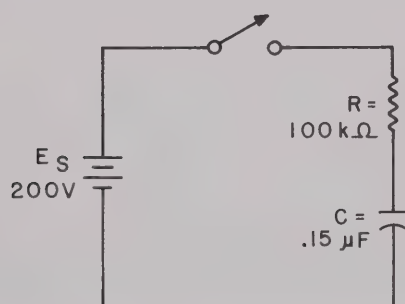
The following Practice Exercise questions cover the subjects which you have just studied. They are:

RC CIRCUITS

RC TIME CONSTANT

CAPACITOR DISCHARGE THROUGH A RESISTOR

13. How many time constants are required for a capacitor to become fully charged or discharged?
14. What is the formula for determining the time constant of an RC circuit?
15. What is the time required for the capacitor to reach full charge in the circuit shown below?



16. How does the voltage across the resistor and capacitor in a series RC circuit vary as the capacitor charges?
17. Does the sum of the voltage drops across the resistor and capacitor in a series RC circuit always equal the source voltage?

18. What happens to the time required for a capacitor to reach full charge if the value of R is increased?
19. What happens to the RC time constant if the source voltage is increased?
20. How does the voltage vary across the resistor and capacitor in Figure 8 during discharge?
21. Assume that R has a value of $10\text{ k}\Omega$ and C has a value of $.25\text{ }\mu\text{F}$ in the circuit of Figure 8. Assuming that the capacitor was charged to 250 volts, what is the capacitor voltage after 3 time constants? How long does it take for the capacitor to fully discharge?

If the RC circuit is replaced by an RL circuit, and switch S manipulated in the same manner to produce the rectangular voltage, E_x , across terminals X and Y, then the rectangular wave alternating voltage is applied to the inductor and resistor in series. Because of the counter emf induced in the inductor, the circuit current rises slowly toward maximum after each change in polarity of E_x .

The voltage across the resistor, which is proportional to the current, may now be shown by the solid line curve in Figure 11A. This voltage rises slowly from 0 toward the positive value of E_x during the time interval from 0 to 1. During the interval from 1 to 2, the circuit current, and therefore the voltage across the resistor, falls quickly to zero and then increases toward the negative value of E_x . During each subsequent interval, the action is repeated in the opposite direction to produce the voltage waveform shown.

Figure 11B now shows the voltage waveform which appears across inductor L. Near the beginning of each interval, when the voltage is changing most rapidly, the back emf is highest and holds the current to a low value. Because of the small current at this time, the voltage across R is very low, and practically all of the applied voltage appears across L.

During each interval, a magnetic field builds up around the inductor, and when E_x drops from maximum to zero, this field collapses to induce an emf which is opposite in polarity to that of the original source. However, at this same instant, E_x reverses its polarity, so that the induced voltage now aids the new E_x . Thus, at points 1, 2, 3, etc., the sum of the induced emf and E_x appears across L, and is equal to nearly twice the E_x voltage after the first two or three alternations.

To summarize, when a rectangular shaped voltage is applied, the solid line curve of Figure 11A indicates the voltage across a capacitor in series with a resistor or else the voltage across a resistor in series with an inductor. In Figure 11B, the solid line curve represents the voltage across a resistor in series with a capacitor, or the voltage across an inductor in series with a resistor. In each instance, the circuit current has the same waveform as the voltage across the resistor.

For any single alternation of the applied rectangular voltage in Figure 11, conditions are the same as though a direct voltage were applied to the RC or RL circuit. The first alternation of E_x causes current and voltage changes like those which occur when a dc voltage is applied with no charge on the capacitor or no magnetic field around the inductor. The remaining alternations produce actions like those that take place when the capacitor is charged, or the inductor has a field built up, at the time that the dc voltage is applied.

The solid line curves of Figure 11 show that neither the currents through nor the voltages across the components have the same waveform as the applied voltage. In the RC circuit, a period of time is required for the capacitor voltage to reach the E_x VOLTAGE each time E_x changes polarity. In the RL circuit, the CURRENT requires a period of time to rise to maximum after each change in E_x polarity. The solid line curve of Figure 11A indicates either the gradual rise of capacitor voltage or RL circuit current.

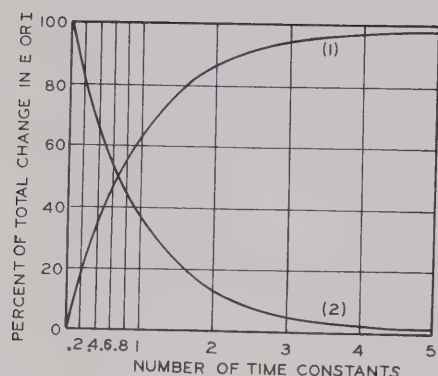


Figure 12

The universal time constant graph of Figure 3 is shown modified slightly in Figure 12. The vertical scale is marked in percent of the total change of either voltage or current, and the horizontal scale is marked in time constants. Curve 1 represents the change in those quantities which begin at zero and rise toward maximum. Curve 2 indicates the change that occurs in those quantities which begin at maximum and fall toward zero. The various quantities which are represented by the curves are as follows:

CURVE 1—

RC Circuit, capacitor voltage.

RL Circuit, resistor voltage and network current.

CURVE 2—

RC Circuit, resistor voltage and network current.

RL Circuit, inductor voltage.

Long and Short Time Constants

The term "frequency" is defined as the number of cycles of alternating voltage or current which occur in one second. This definition applies, regardless of the waveshape of the voltage or current. For the waveform shown in Figure 10B, the voltage E_x is maximum positive at time instant 0. It remains at this value until time instant 1, then changes to maximum negative. At time instant 2, E_x returns to maximum positive, completing one cycle. If E_x completes 50 such cycles each second, it is said to have a frequency, f , of 50 hertz.

With 50 cycles occurring in one second, a single cycle is completed in $1/50$ of a second. The time interval of one cycle is called the **PERIOD**, and is

designated by the letter t . The relationship between period and frequency can be expressed as:

$$t = \frac{1}{f} \quad (3)$$

where: t is the period in seconds, and

f is the frequency in hertz.

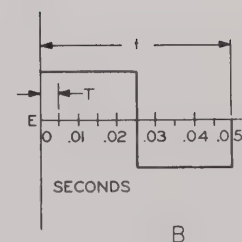
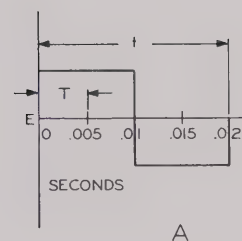
With a frequency of 50 Hz,

$$t = \frac{1}{f}$$

$$= \frac{1}{50} = .02 \text{ second.}$$

Therefore, when the frequency is 50 Hz, the period or time required for one cycle is two-hundredths of a second.

A rectangular voltage wave with a period of .02 second is shown in Figure 13A. The horizontal base line is marked in time units of .005 second each. The first alternation of E requires two such time units, or .01 second, while the complete cycle occupies four time units, or .02 second.



In Figures 13B and 13C, the horizontal base line is numbered in units of .01 second each, and the marks between these numbered units are half of .01 or .005 each. The period of the voltage cycle in Figure 13B is .05 second, and the period of each cycle in Figure 13C is .005 second. In these instances with the period known, the frequency of the applied voltage is determined by:

$$f = \frac{1}{t}$$

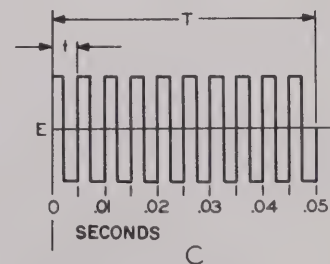


Figure 13

For Figure 13B, with a period of .05 second,

$$f = \frac{1}{t}$$

$$= \frac{1}{.05} = 20 \text{ Hz.}$$

For Figure 13C, with a period of .005 second,

$$f = \frac{1}{t}$$

$$= \frac{1}{.005} = 200 \text{ Hz.}$$

As previously explained, when a rectangular voltage is applied to an RC or RL circuit, the shape of the current and voltage waveforms differs from that of the applied voltage. The amount of waveform change depends upon whether the time constant is short, medium or long, compared to the period of the applied voltage.

Actually, any distinction between short, medium and long time constants is arbitrary but, generally, the practice is to consider that a circuit has a short time constant if the time constant is one-tenth the period of the applied voltage, or shorter. To be classed as a long time constant, the time constant must be at least ten times the period of the applied voltage. Medium time constants are those that fall between these two limits.

If we know the length of the period for a given input waveform, we can predict fairly accurately the output waveform of a given RC or RL circuit. As an example, assume that the voltage of Figure 13A is applied to an RC or RL circuit that has a time constant of .005 second. In this example, the period is .02 second, and the number of time constants per period is .02/.005, or 4. The period of the applied voltage is four times as long as the circuit time constant, which means that the circuit of Figure 13A has a medium time constant.

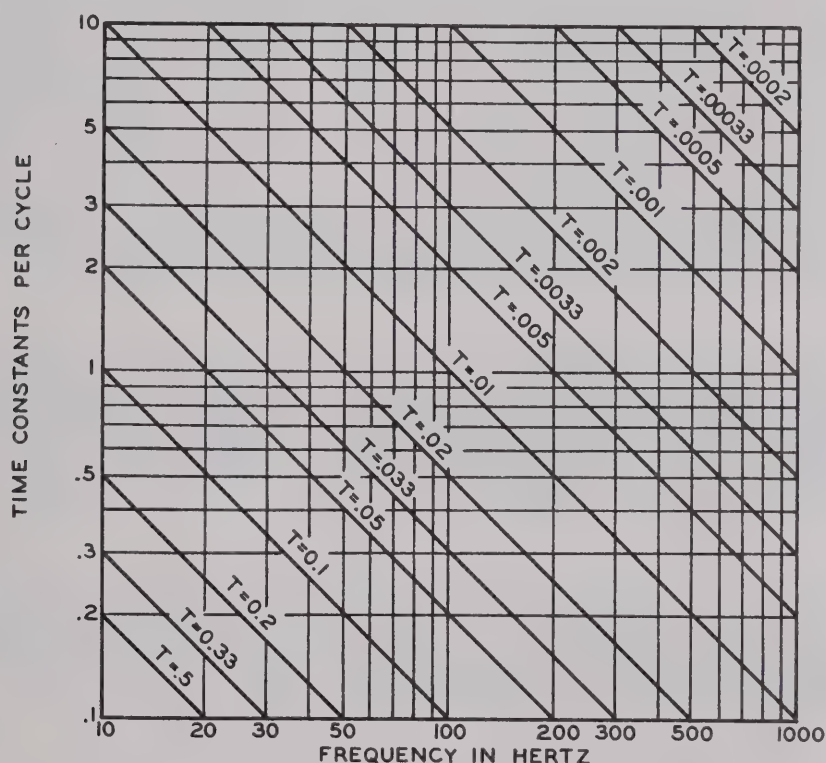
For a second example, assume that the voltage of Figure 13B is applied to a circuit with a time constant of .005 second. The period in this case is .05 second, so the number of time constants per period is .05/.005, or 10. That is, the period is ten times longer than the time constant, or the length

of the time constant is one-tenth the length of the period. This circuit has a short time constant for the applied voltage.

If the voltage of Figure 13C, which has a period of .005 second, is applied to a circuit with a time constant of .05 second, the number of time constants

per period is $\frac{.005}{.05} = .1$, or the time constant is ten times as long as the period.

Thus, the circuit has a long time constant for the applied voltage. The relationship between frequency and time constants is shown in Figure 14.



This graph gives the number of time constants per cycle for various combinations of signal frequency and circuit time constants. After locating the intersection between the diagonal and vertical lines, representing the given time constant (t) and frequency, the position of the intersection is checked with the scale on the left to determine the number of time constants per cycle.

Figure 14

For circuits of a given type, the waveform changes depend upon the number of time constants per period, and not on the actual values of R , C or L . This means that, regardless of the R and C values or R and L values employed in a particular type of circuit, all circuits of this type produce the same effects on the waveform if they have the same number of time constants per period.

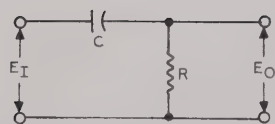
For simplicity, our previous explanations have assumed sinewave or rectangular voltage waveforms of a single or definite frequency. In most electronic applications, the signal voltage waveforms are rather complex. Frequently, these complex forms may be considered as a combination of several sinewave voltages, each of a different frequency. Thus, a single voltage is said to contain both low- and high-frequency components.

According to its effect on the signal voltages and currents, a network is classed as either high pass or low pass. A **HIGH-PASS NETWORK** is one which provides greater output for the high-frequency components of the signal. For example, suppose that a signal is composed of three sinewave components with frequencies of 1000, 2000 and 3000 Hz, all with the same amplitude. If this signal is applied to a high-pass network that is designed to pass signals above 2500 Hz, the 3000-Hz component will have greater amplitude than the 2000-Hz component at the output of the network. Also, the 2000-Hz component will have greater amplitude than the 1000-Hz component. How much the lower frequency signals are reduced at the network output is dependent upon the design characteristics of the network.

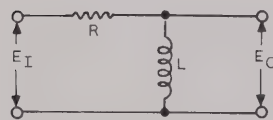
A **LOW-PASS NETWORK** is one which provides a greater output for the low-frequency components of the signal. If the above three-component signal is applied to a low-pass network that is designed to pass signals below 2500 Hz, the 1000-Hz component will have the highest and the 3000-Hz component the lowest amplitudes of the output of the network.

Thus, both the high- and the low-pass networks cause changes in the relative amplitudes of the components of the signals applied to them. These changes in component amplitude result in changes in the waveform of the signal voltage.

RC or RL circuits may be employed either as high-pass or low-pass networks, depending upon the connections used. The effects produced by the network, called the **RESPONSE**, depend upon the arrangement of the circuit as well as the number of time constants per period.



A



B

Figure
15

HIGH-PASS NETWORKS

In the arrangement shown, the RC circuit of Figure 15A functions as a high-pass network. The input signal voltage, E_I , is applied to the capacitor, C, and resistor, R, in series, and the voltage across R forms the output voltage, E_O . Due to its arrangement, the RL circuit of Figure 15B also operates as a high-pass network. Here, the input voltage E_I is applied to

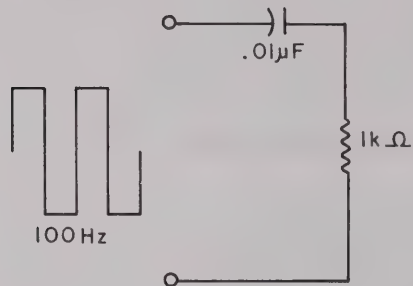
The following Practice Exercise questions cover the subjects which you have just studied. They are:

AC EFFECTS

LONG AND SHORT TIME CONSTANTS

22. Explain the waveshapes of Figure 11 with respect to the circuit of Figure 10.
23. Why is the maximum voltage across the resistor twice the value of source voltage, as shown in Figure 11B?
24. In an RL circuit, when a rectangular source voltage is applied, the waveform of Figure 11_____ represents the voltage across the inductor and the waveform of Figure 11_____ represents the voltage across the resistor.
25. Why is the voltage across the inductor greater than the source voltage when the source voltage reverses polarity, as shown in Figure 11B?
26. Suppose you wished to obtain a peaked waveform like that shown in Figure 11B from a rectangular waveform. How would you obtain this waveform using an RC circuit and an RL circuit?
27. What is the period of a 1 kHz voltage?
28. How would you define a long time constant and a short time constant with respect to the period?

29. In the circuit shown below, is the time constant long or short?



30 What is the difference between a high-pass network and a low-pass network?

resistor R and inductor L in series, and the voltage across L forms the circuit output voltage, E_o .

Response to Rectangular Waves

When a rectangular wave voltage is applied to the input of either of the high-pass networks of Figure 15, the exact shape of the output voltage depends upon the circuit time constant and waveform period relationship, in Figure 16. The dashed line, E_i , indicates the input voltage and the solid line represents the output, E_o .

Figure 16A shows the output response obtained from either network of Figure 15 when each cycle of a square-wave input is ten times as long as the time constant of the circuit (short time constant). Each half-cycle alternation is 5 time constants long. With a short time constant, the capacitor in an RC circuit becomes almost fully charged, and in an RL circuit the current almost reaches its final value.

If the circuit components are selected to provide a medium time constant, with each cycle of E_i occupying a time interval equal to two time constants, the high-pass network has an output voltage, E_o , as shown in Figure 16B. Here, with 2 time constants per cycle, each alternation of E_i exists for 1 time constant. The output is greater because, in the RC circuit, the capacitor is still charging, and the current through R causes a voltage drop across the resistor. In the RL circuit the impedance across L is still large enough to cause a voltage drop across the inductor. This is because the resistor voltage in an RC circuit and the inductor voltage in an RL circuit fall to about 36.8% of their initial values during the first time constant. Therefore, as shown in Figure 16B, at the end of each alternation, E_o falls to about 36.8% of the peak voltage that occurs at the beginning of the alternation. When a long time constant is used, the output waveform is like Figure 16C. Here, one alternation of E_i is equal in duration to only two-tenths of a time constant. The output voltage only falls to about 78% of its initial peak during this relatively short interval. THE OUTPUT VOLTAGE WAVEFORM IS NOT MUCH DIFFERENT FROM THE INPUT VOLTAGE WAVEFORM.

For either of the high-pass networks of Figure 15, with a rectangular voltage input waveform of a given frequency, any of the output waves shown in Figure 16 may be obtained by selecting circuit values to give the desired time constant. An important point to remember is that THE RESULTING OUTPUT WAVEFORM DEPENDS UPON THE NUMBER OF TIME CONSTANTS PER PERIOD, rather than upon the signal frequency or circuit time constant alone.

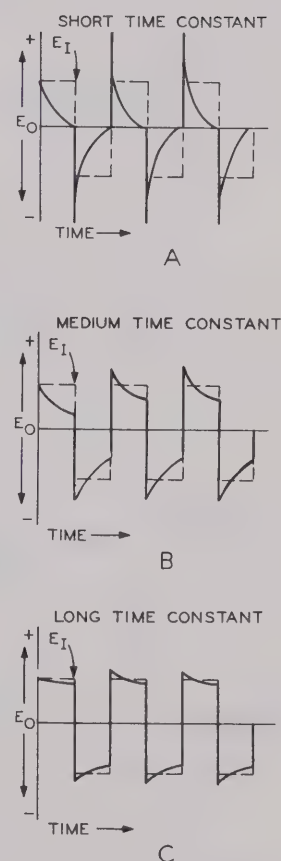


Figure 16

After the first alternation of an applied voltage, the circuit develops a counter emf which adds to the applied voltage. In the RC circuit, this emf is due to the charge stored in the capacitor, and in the RL circuit it is due to the energy stored in the magnetic field around the inductor. Therefore, at the beginning of each alternation following the first one, this emf adds to E_I , making the effective applied voltage larger than E_I alone.

If the time constant is short, a large quantity of energy can be stored during each alternation because the capacitor reaches maximum voltage in the RC circuit, and the current reaches near maximum in the RL circuit. Therefore, at the start of an alternation in an RC circuit such as that of Figure 15A, the large capacitor voltage adds to E_I , producing a heavy initial current with a resulting large voltage across R. At the start of an alternation in the RL circuit of Figure 15B, the strong collapsing field induces a large voltage across L; and this voltage adds to E_I , appearing almost entirely across the inductor at this time.

For both circuits, the output voltage, E_O , has a relatively high value at the beginning of each alternation, as shown in Figure 16A. The voltage peaks increase for the first few alternations until an equilibrium is reached, after which all peaks have the same magnitude.

If the time constant is medium, there are few time constants per cycle. Therefore, the RC circuit capacitor cannot charge to as high a voltage during each alternation of E_I , and the RL circuit current cannot rise to a high value to produce a strong magnetic field about the inductor. The energy stored in the network is less and, when added to E_I at the beginning of each alternation, results in a lower equivalent applied voltage. Thus, as shown in Figure 16B, at the beginning of each alternation after the first one, the E_O peak is lower than in Figure 16A.

Representing conditions in which there are only 0.4 time constants per cycle, the E_O curve in Figure 16C rises slightly above E_I at the beginning of each alternation. In this case, the alternations of E_I are so short compared to the circuit time constant that the capacitor in the circuit of Figure 15A charges only slightly during each alternation, and in the circuit of Figure 15B the current reaches a relatively low value.

Summarizing the various actions indicated by the curves of Figure 16: when a rectangular wave voltage is applied to an RC or RL circuit, the circuit voltage and current waveform change the most when there are many time constants per cycle. As a result, in high-pass networks, the output waveform is considerably different from the input waveform when the time constant is short, and the output and input waveforms are nearly alike for long time constants.

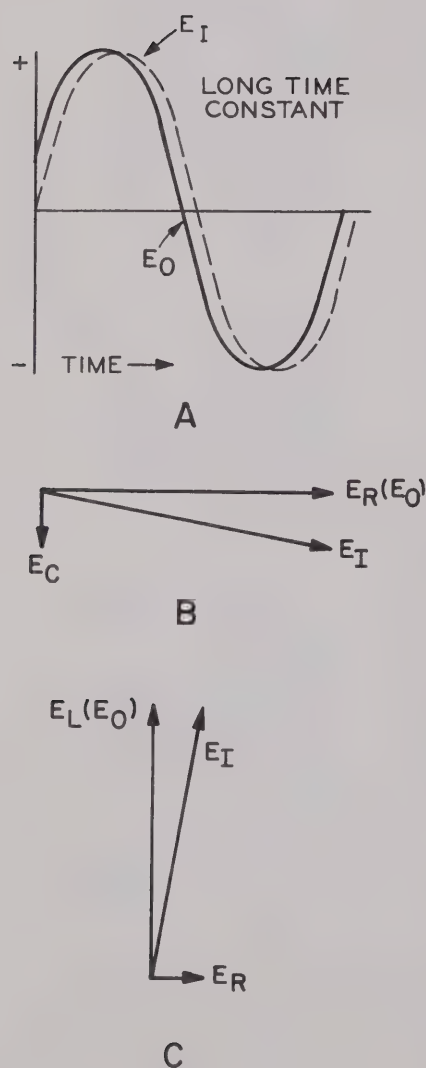
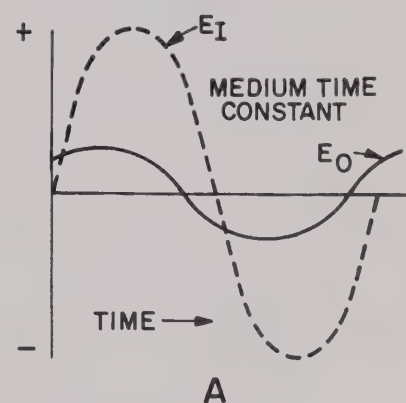


Figure 17

Response to Sinewaves

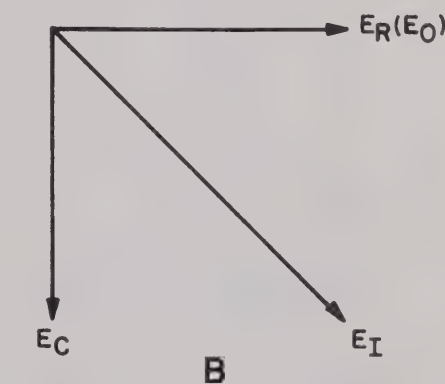
When a sinewave input voltage is applied to a high-pass network like Figure 15A or 15B, the output waveshape is not changed. However, the output voltage, E_o , has less amplitude and is shifted in phase, when compared to the applied voltage, E_i . These changes are illustrated in the following text and figures for the three different time constants. The solid line curves represent the output voltage, E_o , and the dashed line curves represent the applied voltage, E_i .

In an RC high-pass filter with a long time constant, the output voltage, E_o , is almost as large as the input voltage, E_i , and the output is also almost in phase with the input, as shown in Figure 17A. With a long time constant, X_C will be small, and most of the circuit voltage will be across R , at the output. If the voltage drop across the capacitor, E_C , and the voltage drop across the resistor, E_R , are added vectorially, as in Figure 17B, the resultant vector is equal to the voltage amplitude and direction of the input voltage, E_i . In this circuit, there is little difference between the amplitudes and directions of E_i and E_R . The output voltage, E_o , is also the voltage across the resistor, E_R .



The small difference shows that there is little phase shift or amplitude reduction of E_o , compared with E_i . The vectors also show that the phase of E_o slightly leads that of E_i .

In an RL high-pass circuit with a long time constant, X_L will be large compared to R , causing the voltage drop across the inductor, E_L , to be large compared to the voltage drop across the resistor, E_R , as shown in Figure 17C. In this circuit, the output, E_o , is across the inductor. Again, E_o is almost as large as E_i , and E_o again slightly leads E_i in phase.



In Figure 18A, the phase and amplitude relationships between E_i and E_o are shown for a medium time constant high-pass circuit. E_o is now smaller than E_i , and has greater phase shift.

The voltage vectors for a medium time constant RC high-pass circuit are shown in Figure 18B. The output voltage, E_o , taken across R , is smaller because of the greater X_C that causes more voltage drop across the smaller value capacitor. The vector sum, E_i , is also at a greater displacement angle from E_R . The output, taken across R , now has less amplitude and greater phase shift than in the long time constant circuit.

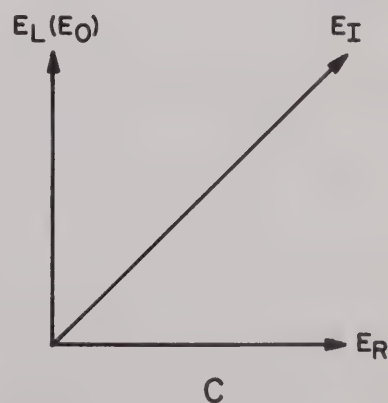
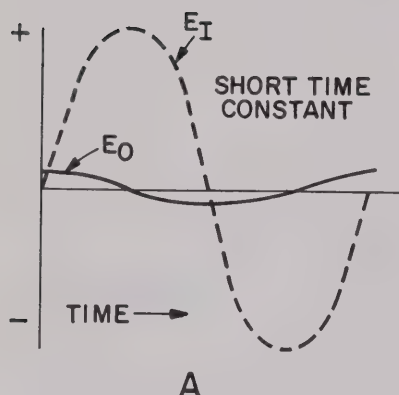
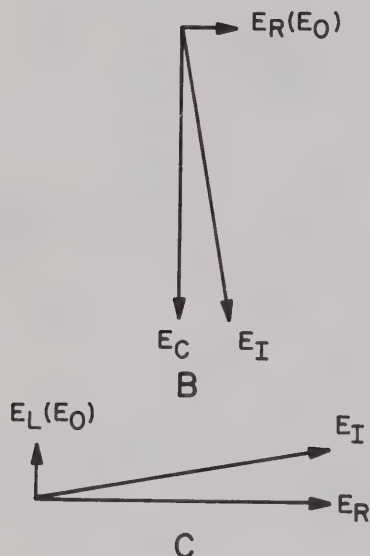


Figure 18



The voltage vectors for a medium time constant RL high-pass circuit are shown in Figure 18C. The output, E_o , taken across the smaller inductor, has less amplitude and greater phase shift than in the long time constant circuit.

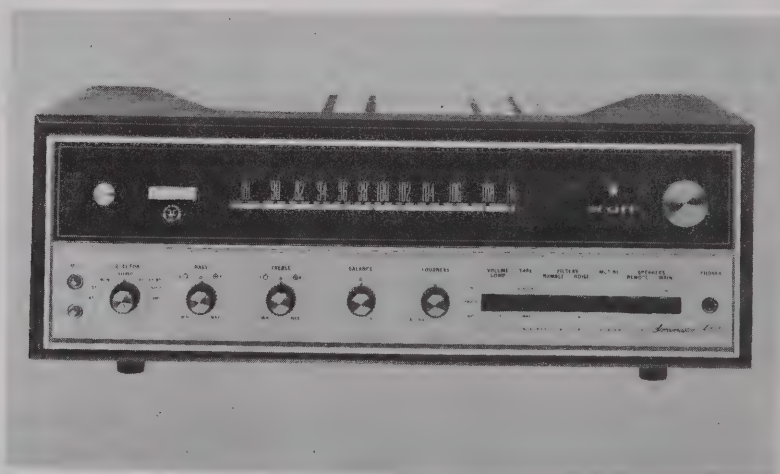
In Figure 19A, the phase and amplitude relationships between E_I and E_o are shown for a short time constant high-pass circuit. E_o is now much smaller than E_I , and has almost 90° of phase shift. The voltage vectors for a short time constant RC high-pass circuit are shown in Figure 19B. The output voltage, E_o , taken across R , is quite small because of the large X_C of the small value capacitor. The vector sum, E_I , is now greatly displaced from the angular direction of E_R . The output, besides being quite small, is therefore almost 90° out-of-phase with E_I .



The voltage vectors for a short time constant RL high-pass circuit are shown in Figure 19C. The output, E_o , taken across the small value inductor, is quite low, and almost 90° out-of-phase with E_I .

The difference in amplitude between E_I and E_o in a high-pass network depends not only on the circuit time constant, but also on the size relationship between the circuit's resistive and reactive components. If the capacitor has a large value compared to the resistor value, there will be a larger voltage

Figure 19



An FM receiver such as the one shown above employs a low-pass filter circuit called a "de-emphasis network." This circuit has a time constant of 75 microseconds and is employed to provide uniform frequency response over the audio-frequency range.

Courtesy H. H. Scott

drop across the resistor, resulting in a larger output voltage. In a high-pass RL network, if the value of L is large compared to the value of R , more voltage will then be dropped across the inductor, again resulting in a larger output voltage.

Comparing the waveforms of Figures 17, 18 and 19 with those of Figure 16, when E_i has a sinewave form, the output E_o has greater amplitude under conditions of a long time constant, whereas, when E_i has a rectangular waveform, the output peaks have greater magnitude in the case of a short time constant. For either waveform, E_o differs the least from E_i when the time constant is long.

In the various applications of high-pass networks, the choice of a time constant depends upon the output waveform, amplitude or phase shift desired. Thus, if the voltage is to be passed by these networks with minimum change or distortion for either rectangular or sinewave input voltages, circuit values must be selected to provide a relatively long time constant. Short time constants are required when sharp pulses are desired, or when a large phase shift or reduction in amplitude of a sinewave is needed.

LOW-PASS NETWORKS

With the positions of its R and C components reversed with respect to Figure 15A, the circuit of Figure 20A functions as a low-pass network. Again, the input voltage, E_i , is applied to the resistor, R , and the capacitor, C , in series, but now the voltage across C forms the output voltage, E_o . Because of the rearrangement of components compared with Figure 15B, the RL circuit of Figure 20B also functions as a low-pass network. The input voltage, E_i , is applied to the inductor, L , and the resistor, R , in series, but the voltage across R forms the output voltage, E_o .

Response to Rectangular Waves

When a rectangular wave voltage is applied to the input terminals of either of the low-pass networks of Figure 20, the time constant again determines the exact waveform of the output voltage. Three examples are given in Figure 21, where the output, E_o , is represented by the solid line curves and the input, E_i , by the dashed line curves.

For a circuit with a short time constant, E_o has the waveform shown in Figure 21A. In this example, one alternation of E_i is equal to 15 time constants. It requires only one-third of this time, or 5 time constants, for the

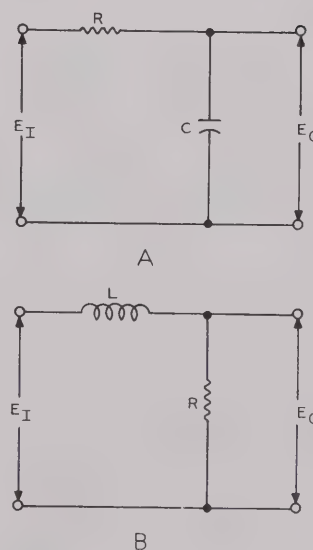


Figure 20

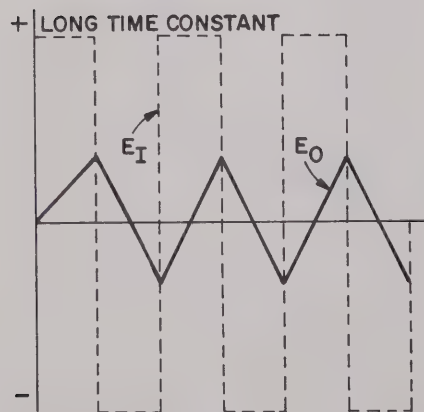
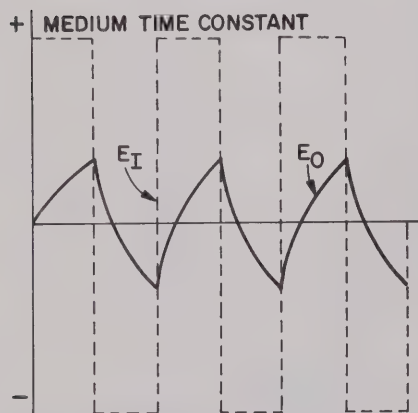
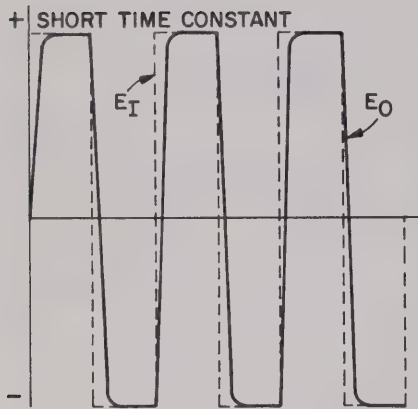


Figure 21

capacitor voltage in an RC circuit or the current in an RL circuit to reach what is approximately its final value. Therefore, the E_O curve rises to equal the value of E_I in about one-third the time of one alternation. Thus, due to its relatively rapid rise, E_O has a waveform which does not differ greatly from that of E_I .

For a circuit with a medium time constant, the output voltage waveform after a few cycles is as shown in Figure 21B. In this example, the duration of each E_I alternation is equal to one circuit time constant. Therefore, E_O does not rise to the full value of E_I .

For a circuit with a long time constant, the output voltage waveform after a few cycles is as shown in Figure 21C. Here, there are 10 E_I alternations to each circuit time constant, and the output voltage, E_O , will rise only to a small fraction of the input voltage, E_I .

For rectangular voltages, a low-pass network has an output waveform most like the input when the time constant is short, unlike the high-pass network in which E_O and E_I are most alike when the time constant is long. The waveforms are the same ones that are present in high-pass networks. The difference in output waveshapes results from the fact that the outputs are taken across the opposite components in low-pass networks. The output is across the capacitor in a low-pass RC network, and the output is across the resistor in a low-pass RL network.

Response to Sinewaves

When the input voltage, E_I , has a sinusoidal waveform, the low-pass networks of Figure 20 have sinewave outputs, but the magnitude and phase of E_O with respect to E_I depends upon the circuit time constant.

The effects of different time constants are shown in Figure 22. In Figure 22A, the curves indicate the difference between E_I and E_O for a low-pass network with a short time constant. For a similar network with a medium time constant, the difference between E_I and E_O is shown by the curves of Figure 22B. A circuit with a long time constant produces the difference shown by the curves of Figure 22C. Notice particularly how the curves differ in both magnitude and phase.

The large X_C of the small value capacitor in a short time constant RC circuit low-pass network causes a large voltage drop across C. This large voltage drop is also the output voltage, since the output of this circuit is taken across

C. Here, E_o lags E_i , since in the capacitive circuit of Figure 20A, the capacitor voltage, E_o , lags the circuit voltage, E_i . However, vector addition of the circuit voltages shows that a large capacitor voltage vector, E_c , will not be much out-of-phase with the vector for E_i .

For a short time constant RL low-pass network, the small inductance causes most of the circuit voltage drop to occur across the resistor. This causes a large output voltage, since in this circuit the output is taken across R. The large voltage vector of the resistor, E_R , slightly lags the phase of the vector of E_i , again resulting in a slight phase lag of the output voltage.

For a medium time constant low-pass network, E_o is considerably less than that of E_i , and there is a greater lagging phase shift between E_o and E_i , as shown in Figure 22B. For a long time constant, as shown in Figure 22C, the amplitude of E_o is much less than that of E_i , with a still greater phase shift between E_o and E_i .

What type of low-pass circuit should be used in a given application depends upon the waveform change desired. As the curves of Figures 21 and 22 show, to obtain a minimum of waveform distortion, amplitude reduction or phase shift, conditions which provide relatively short time constants are required. Circuits which provide long time constants must be used when it is desired to produce triangular waves, or to reduce the amplitude or shift the phase of a sinewave voltage.

Comparing the actions in the low-pass and high-pass networks, we find that the conditions required to achieve minimums of distortion, amplitude, reduction and phase shift when using low-pass networks are the opposite of those required for high-pass networks. To obtain these characteristics, the low-pass networks require conditions producing relatively short time constants; however, conditions providing relatively long time constants are required for the high-pass networks. When it is desired to produce maximum changes of waveforms, reduction in amplitude or increases in phase shift, short time constants must be used in high-pass networks and long time constants used in low-pass networks.

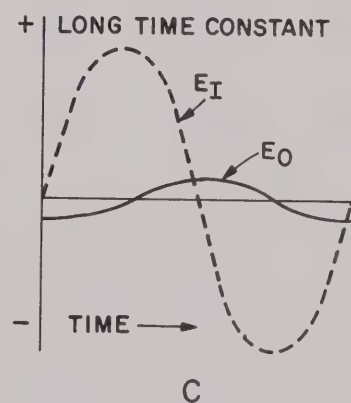
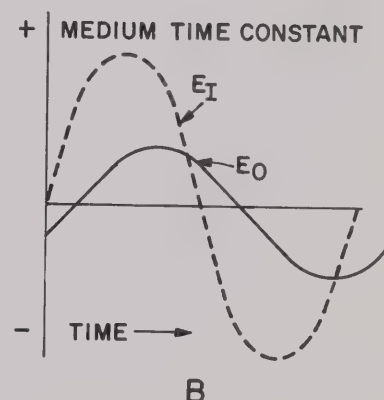
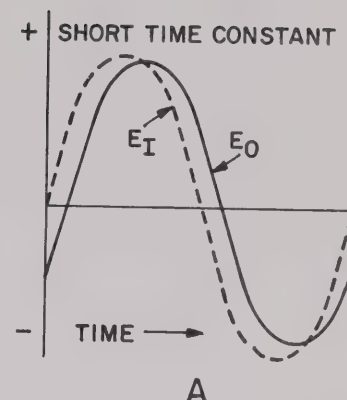


Figure 22

FILTERS

In many electronic applications, only selected bands of signal frequencies are used. For such applications, **FILTERS** are used to obtain the desired signals and reject or eliminate unwanted signals. A filter is a selective network which passes alternating currents or voltages within a given band of

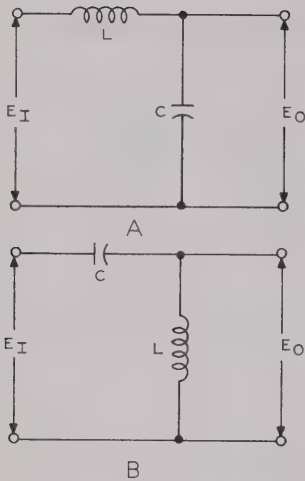


Figure 23

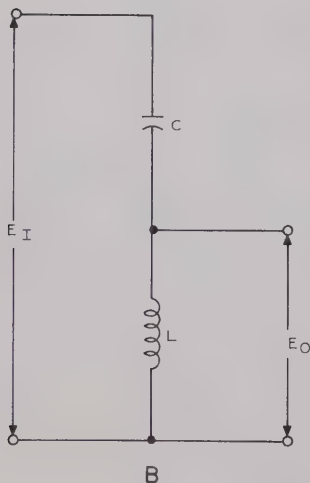
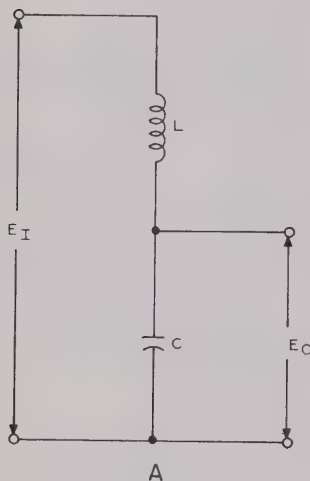


Figure 24

frequencies, and provides considerable reduction in the magnitudes of currents or voltages at other frequencies. If direct current is considered an alternating current of zero frequency, then filters also include those devices that are employed to pass or reject dc.

The RC and RL high-pass and low-pass networks described previously are types of filters. Other quite common types of filters are **LC NETWORKS**, shown in Figure 23.

BASIC LC FILTER

The basic function of this type of filter is to divide the input voltage into two portions and use one as the output. This action can be more easily understood if we examine these filters as they are redrawn in Figure 24. The input voltage, E_I , is applied to inductor L and capacitor C in series. The difference in the two types of circuits is that the output, E_O , is the voltage across capacitor C in Figure 23A and Figure 24A, and across inductor L in Figure 23B and Figure 24B.

When there is an increase in frequency of the applied ac voltage, inductive reactance increases and capacitive reactance decreases. Therefore, the output voltage, E_O , is affected by the frequency of the input voltage, E_I . Inductive reactance, X_L , and capacitive reactance, X_C , are directly opposing quantities. The total reactance of a series circuit is equal to the difference between X_L and X_C .

At low frequencies, inductor L has very little reactance, and the reactance of capacitor C is quite high. Therefore, the output voltage for Figure 24A is large since it is taken from across the capacitor, and the output for Figure 24B is small since it appears across the inductor. At high frequencies, inductor L has a large reactance, and capacitor C has a low reactance. Now conditions are reversed; the output is low for Figure 24A and high for Figure 24B. It turns out, then, that these filters are also high- and low-pass networks. Figure 24A is a low-pass filter and Figure 24B is a high-pass filter.

For both circuits, the output voltage, E_O , has relatively large magnitude when the component connected across the output terminals has large reactance compared with that of the component that is in series between E_I and E_O . Thus, for a maximum transfer of signal at a given frequency, X_C should be large compared with X_L in the circuit of Figure 24A, and X_L should be large in the circuit of Figure 24B.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

HIGH-PASS NETWORKS

RESPONSE TO RECTANGULAR WAVES

RESPONSE TO SINEWAVES

LOW-PASS NETWORKS

RESPONSE TO RECTANGULAR WAVES

RESPONSE TO SINEWAVES

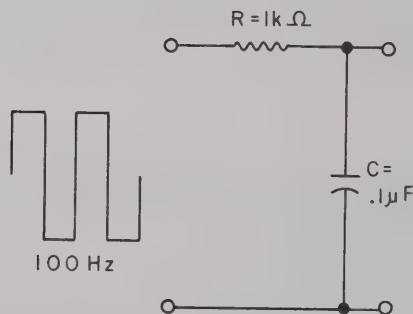
31. To obtain a peaked waveform from a high-pass filter, compared to the period of the rectangular input signal, the time constant should be (a) long, (b) short.
32. In an RL high-pass filter circuit, across which component is a peaked waveform developed when the time constant is short with respect to the period?
33. To pass a rectangular waveshape signal through a high-pass filter without appreciably altering the waveshape, the time constant should be (a) long, (b) short.
34. When a sinewave signal is applied to a high-pass network, is the wave-shape changed?
35. Maximum output from a high-pass filter is obtained with a sinewave input when the time constant is (a) long, (b) short.

36. When a sinewave signal is passed through a high-pass network, the output signal (a) leads the input signal, (b) lags the input signal.

37. Draw the circuit diagrams of RL and RC low-pass networks.

38. What is the output waveshape of a low-pass RC filter with a long time constant when a rectangular waveshape signal is applied to the input?

39. What is the approximate output waveshape from the circuit shown below?



40. To obtain maximum output from a low-pass filter with a sinewave input, the time constant should be (a) long, (b) short.

41. What is the phase relation between input and output of a low-pass network with a sinewave input?

E_o is relatively small when the series-connected component has the larger reactance, and therefore, attenuation is greater at high frequencies in Figure 24A, where X_L is large, and greater at low frequencies in Figure 24B, when X_C is large.

Whatever the values of L and C in a particular application, they form a series-resonant circuit at some frequency, and when E_i is at the resonant frequency, the current is very large due to the low total reactance of the circuit. Consequently, since the voltage across each reactor is equal to its reactance times the current at the resonant frequency, the voltages are large across both inductor and capacitor, and therefore, either type of these circuits may be used to provide the greatest signal magnitude at the resonant frequency.

TYPES OF FILTERS

To meet the needs of various types of electronic equipment, a large number of filter circuit arrangements have been developed. Almost all of these arrangements consist of some type of RC, LC or LCR network, or a combination of such networks. These filters may be classified as low-pass, high-pass, band-pass and band-rejection.

A **LOW-PASS FILTER** is one that freely passes all frequencies from zero up to a certain "cutoff" value, and greatly attenuates all higher frequencies.

A **HIGH-PASS FILTER** is one that rejects all frequencies from zero up to a certain limit but freely passes all higher frequencies.

A **BAND-PASS FILTER** is one that accepts all frequencies between two limits and attenuates all frequencies above and below these limits.

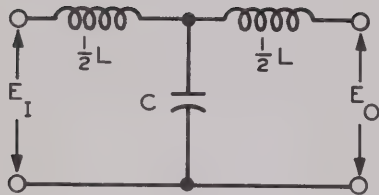
A **BAND-REJECTION FILTER** attenuates all frequencies between certain limits, but freely passes all frequencies above and below these limits.

FILTER CIRCUITS

Filter circuits usually contain series and parallel elements. The actions of these elements depend on the filter arrangements.

L-Section Filter

Figures 23A and 23B are drawn conventionally, but you will notice that, in each figure, one component is drawn in series with the upper line. This component is called the **SERIES IMPEDANCE**. The other component is connected in parallel, or in shunt with the output circuit, and is called the **SHUNT IMPEDANCE**.

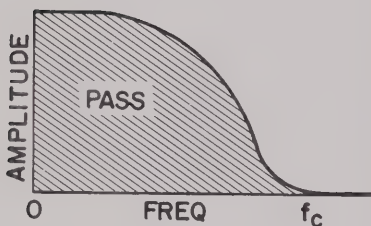


A

In these figures, the series and shunt impedances form the shape of an inverted L. Therefore, the filter is called an **L-SECTION FILTER**.

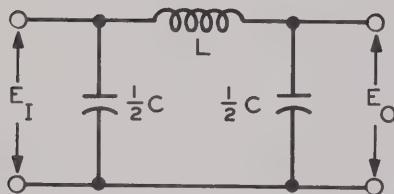
Low-Pass T and Pi Filters

Notice that, in Figure 25A, two coils, $\frac{1}{2} L$, are connected in series to form the flat top of a "T", and the shunt capacitor, C forms the stem of the "T". In Figure 25C, each capacitor, $\frac{1}{2} C$, forms the vertical stems of the Greek letter π (Pi) and the coil, L, forms the flat top.



B

The action of the low-pass T and π filters is such that the series inductance arms offer low impedance to the low-frequency currents and high impedance to the high-frequencies, and the shunt capacitors present low-impedance paths to the high-frequency currents and high-impedance paths to the low frequencies.



C

Figure 25

As used in the paragraph above, the expressions "low" and "high" are relative terms and have no exact meaning. Therefore, for low-pass filters of this type, it is convenient to choose some reference, called the **CUTOFF FREQUENCY** (f_c), below which the desired transmission is obtained, and above which the signals are reduced or attenuated. With a selected cutoff frequency, the combined actions of the series and shunt impedances can be expressed in terms of the degree of attenuation, relative to the cutoff frequency, which the entire filter produces at any other frequency.

A filter like that in Figure 25A has a frequency attenuation characteristic, as shown by the curve of Figure 25B. The horizontal scale indicates frequency, increasing from zero at the left, to above f_c at the right. The signal amplitude is indicated by the vertical scale at the left.

Starting at the left, there is no attenuation at frequencies almost up to cutoff at f_c . Going further to the right, at frequencies above f_c the attenuation increases rapidly at first and then more slowly as higher frequencies are reached.

Because the filter output reduces as the attenuation increases, the frequencies below f_c are called the pass or transmission band, and those higher than f_c form the reject or attenuation band.

Figure 25C illustrates a pi-section, low-pass filter in which a single inductor comprises the series impedance and two capacitors form the shunt impedance. The action of this filter is similar to that of Figure 25A, where the series and shunt impedances offered to various frequencies are concerned. Therefore, the attenuation curve of Figure 25B applies equally well to the T- and pi-section low-pass filters of Figure 25A and 25C.

High-Pass T and Pi Filters

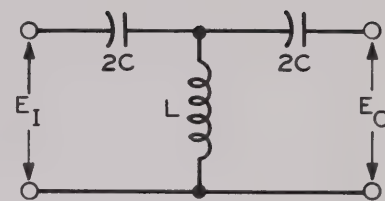
High-pass T- and pi-section LC filters are shown in Figures 26A and 26C, respectively, with their attenuation curve in Figure 26B. In these networks, the series capacitors present low impedance to high frequencies and high impedance to low frequencies, while the shunt inductors present high impedance to high frequencies and low impedance to low frequencies. From the shape of the reject and pass bands, we see that high-pass filters work opposite to low-pass filters.

RC AND RL FILTERS

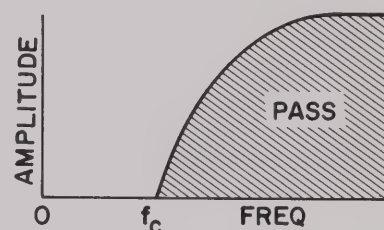
Although LC filters are shown in the high-pass and low-pass circuits of Figure 23, RC and RL combinations can also be used. For example, by replacing the inductor of Figure 23A with a resistor, the circuit remains a low-pass filter. Although the resistance of R remains the same, the capacitive reactance still reduces with frequency increase. As a result, as the frequency goes up, the output voltage goes down; that is, the attenuation increases.

Similarly, if the capacitor of Figure 23B is replaced by a resistor, the circuit still functions as a high-pass filter. Since the inductive reactance increases with frequency, the output voltage increases. Consequently, either the capacitors or the inductors shown in the circuits of Figures 25 and 26 can be replaced by resistors, without altering the high- or low-pass characteristics.

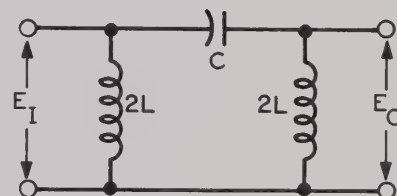
However, when a reactance is replaced by a resistor, the difference in attenuation between the pass and rejection band is not as great, and the band of frequencies covered during the change from pass to rejection is broader. Nevertheless, due to light weight, compactness and economy, resistors are often used in preference to inductors for filters of these types. In fact, the RC filter is found in most electronic equipment.



A



B



C

Figure 26

APPLICATIONS OF NETWORKS

It would be impossible to describe here all of the many applications for simple high-pass and low-pass networks. However, some of these applications are so basic that they are used in practically every type of electronic circuit.

Power Supply Filter

Figure 27 shows a power supply circuit in which an RC filter reduces the variations in the output voltage. Resistor R_1 and capacitors C_1 and C_2 form a low-pass filter, using R_1 in place of an inductor. The purpose of this filter is to attenuate all alternating voltage components and pass only direct voltage. The values of R and C are dependent on the frequency of the pulsations of the rectifier output. This frequency is called the ripple frequency.

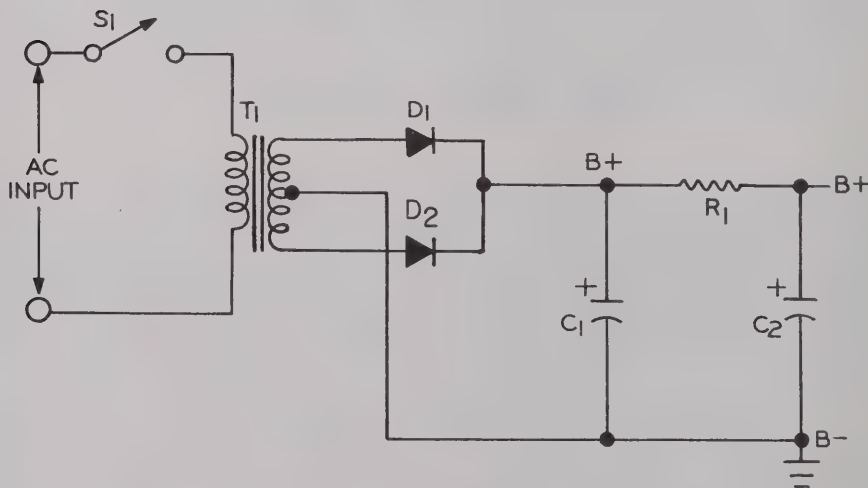


Figure 27

In the circuit of Figure 27, the filtering may be considered to consist of two actions. The first is that in which C_1 is charged by the conduction of diodes D_1 and D_2 in series with alternate halves of the secondary winding of T_1 , and then discharges through the external load. For the second action, the voltage variations across C_1 are attenuated by R_1 and C_2 , which together form an L-type filter.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

FILTERS

BASIC LC FILTER

TYPES OF FILTERS

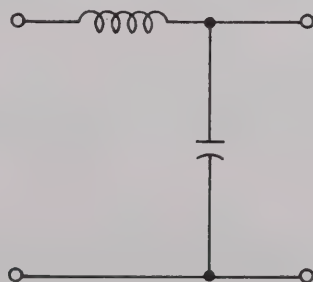
FILTER CIRCUITS

L-SECTION FILTER

LOW-PASS T AND PI FILTERS

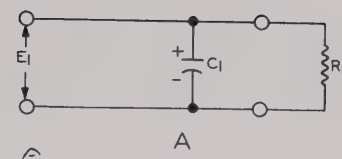
HIGH-PASS T AND PI FILTERS

42. What is a filter?
43. In the circuits of Figures 23A and 23B, when is the output voltage maximum?
44. How does a band-pass filter differ from a band-rejection filter?
45. If you desired to attenuate all signal frequencies above a certain frequency, what type of filter would you employ?
46. Identify the series and shunt impedances in the filter circuit shown below.



47. Draw T-type and π -type LC low-pass filters.
48. What is the cutoff frequency with respect to a low-pass filter?
49. Below the cutoff frequency in a π -type LC low-pass filter, is X_L high or low with respect to X_C ?
50. Draw T-type and π -type LC high-pass filters.

Figure 28A shows C_1 without R_1 and C_2 , and resistor R_L connected across the filter output terminals to represent the external load. The rectifier circuit supplies the output to C_1 . When the rectifier is conducting, its total current divides so that part charges C_1 and the remainder passes through R_L to maintain the load current.



For any given ripple frequency, the larger the $R_L C_1$ time constant, the greater the degree of filtering obtained. However, the value of R_L is sometimes fixed by the circuits in any given application. Therefore, any increase in the time constant must be obtained by increasing the capacitance of C_1 . In turn, the maximum value of C_1 is limited by the peak current rating of the rectifier. In some cases where the load current is small, or a great degree of filtering is not required, only the single shunt capacitor, C_1 , is needed. However, larger load currents or better filtering require that the L section, $R_1 C_2$, be added.

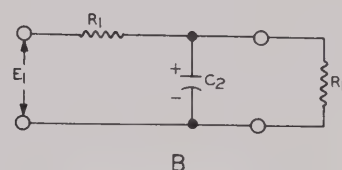


Figure 28

Figure 28B shows the L-type filter section with load R_L connected across its output terminals. To study the filtering action of this circuit, you can consider input capacitor C_1 as part of the rectifier system. Then, the voltage developed across C_1 is the voltage applied to the input of the L-type filter of Figure 28B. The voltage across C_2 is the output voltage of the power supply. When the applied C_1 voltage increases, C_2 charges through R_1 . As C_1 discharges and its voltage decreases, C_2 discharges through R_L . If the time constant $R_1 C_2$ is large, the increases of the C_1 voltage cause little increase in the voltage across C_2 . Also, if the time constant $R_1 C_2$ is large, the voltage across C_2 decreases only slightly when the C_1 voltage falls. In the charge circuit, the resistance of R_1 is limited by the amount that the voltage across the resistance can be allowed to reduce the output of the power supply. Since R_L is fixed by the load circuits, C_2 must have a large capacitance to provide the long time constant.

Attenuation Equalizers

As explained, a filter is a network which attenuates all frequencies above or below the pass band, but provides fairly constant output at all frequencies within the pass band. However, few filters or other types of transmission networks are capable of providing the degree of constant output required for certain applications. Usually, undesired attenuation occurs even within the pass band. To compensate for this, a network known as an **ATTENUATION EQUALIZER** is employed.

Assume that a signal having uniform amplitude over the band from 50 to 10,000 Hz is applied to a circuit which provides an increasing response at



Tape recorders employ various equalizer networks to provide uniform frequency response for different tape speeds.

Courtesy Bell & Howell

frequencies above 1000 Hz. If uniform, or "flat," response is desired, it may be obtained by inserting an equalizer with an attenuation characteristic which rises above 1000 Hz at the same rate as the response of the circuit increases. Thus, at any given frequency, the attenuation of the signal energy in the equalizer cancels the undesired increase in circuit response.

Conversely, should a coupling network or transmission line attenuate the signal undesirably at either end of the pass band, an equalizer may be employed to provide corresponding attenuation through the remainder of the pass band. By this method, frequencies over the entire band are attenuated equally and a uniform output is obtained, which may be amplified to compensate for the losses.

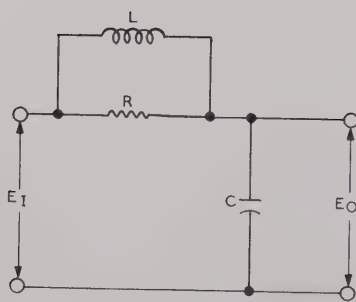


Figure
29

An attenuation equalizer may consist of any network like those explained earlier in this lesson. A modification of one type is shown in Figure 29. This equalizer employs an LC type L-section configuration with resistor R added in parallel with the series impedance element, L. Resistor, R, maintains a constant impedance, Z, which the equalizer network presents at its input terminals. In practice, R is made equal in value to the equal impedance

of the external input circuit, signal source and the external output circuit, or load between which the equalizer is connected.

In the circuit of Figure 29, the reactances of coil L and capacitor C are equal to each other and also to the resistance, R , at a certain frequency, f_c . That is, when the applied voltage E_I has a frequency f equal to f_c , the circuit relationships are: $X_L = X_C = R$. From these relationships, it is possible to calculate the L and C required to produce a specific attenuation at the frequency f_c .

For example:

$$X_L = 2\pi f_c L \text{ and } X_C = \frac{1}{2\pi f_c C}$$

but as $X_L = X_C = R$:

$$R = 2\pi f_c L \text{ and } R = \frac{1}{2\pi f_c C}$$

Rearranging the terms,

$$L = \frac{R}{2\pi f_c} \text{ and } C = \frac{1}{2\pi f_c R}$$

For any given application, the value of f_c is determined by the frequency range over which equalization is desired, and R is determined by the impedances of the source and load between which the equalizing network is to be connected.

For the circuit of Figure 29, X_L is greater and X_C is less than R at frequencies above f_c , while at frequencies below f_c , X_L is less and X_C is greater than R . As the frequency of E_I increases, the voltage drop across the series arm L becomes greater and that across the shunt arm C becomes less, causing the output voltage E_O to fall. Hence, the attenuation of the signal increases with increasing frequency.

For the circuit of Figure 30, the conditions are reversed. As the frequency increases, the voltage drop across L becomes greater and that across C becomes less, and the output voltage rises because L and C form a high-pass filter.

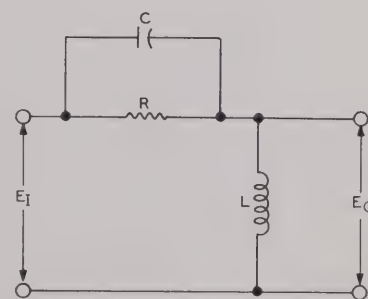
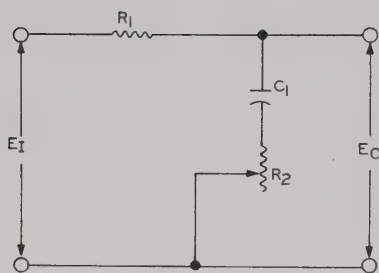


Figure 30

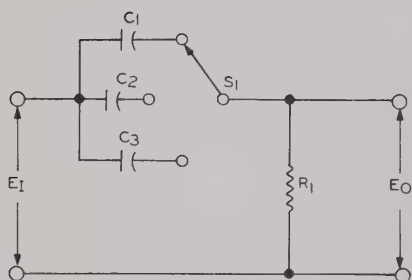
Variable Equalizers

Often it is desirable to vary the equalization to meet needs which change from time to time. For example, two radar sets located close to each other, but operating on different frequencies, tend to interfere with each other. When this happens, undesirable signals are displayed on the radar indicator and tend to confuse the radar operator. To eliminate this interference, it is customary to employ a variable equalizer called an INTERFERENCE SUPPRESSOR, two circuits of which are shown in Figure 31.



A

The circuit of Figure 31A consists of an L-section RC low-pass network with a variable resistor, R_2 , in series with the capacitor, C_1 , in the shunt arm. Basically, the R_1C_1 network provides an output, E_0 , which decreases in amplitude with signal frequency increases, as explained earlier in the lesson for Figure 24A.



B

Figure 31

Resistor R_2 permits reducing the effect of C_1 in the circuit. By moving the slider to increase the resistance in the circuit, an increasingly larger portion of E_0 appears across R_2 , and less and less appears across C_1 . Since the voltage across a resistor does not vary with frequency, the high frequencies in the signal are not attenuated by the resistor much more than the lows. When the value of R_2 is large compared to X_{C_1} , the reactance has little effect, and the circuit may be considered a resistance voltage divider, R_1R_2 , with E_0 taken across R_2 .

When the slider is moved to reduce the amount of R_2 in the circuit, the voltage across C_1 becomes an increasingly larger portion of E_0 . Since X_{C_1} varies inversely with frequency, the higher frequency components of E_0 now are attenuated more than the lows, giving the usual low-pass filter action. Thus, by adjusting the R_2 slider, the high-frequency attenuation produced by the network in Figure 31A is changed.

Another variable equalizer is the L-section RC high-pass network shown in Figure 31B. Here, switch S_1 selects any one of the three capacitors to form the series arm, and resistor R_1 is the shunt arm. Since capacitive reactance varies inversely with frequency, in the circuit of Figure 31B the reactance of the series arm is greater for the lower frequency components of E_1 .

The amount of attenuation produced by an equalizer of this type is proportional to the impedance of the series arm. Therefore, for any setting of S_1 , the attenuation varies inversely with frequency. However, with different capacitance values for C_1 , C_2 and C_3 , the attenuation is different at any given frequency for different settings of S_1 . Thus, a decrease of signal for the lower frequencies is controlled by switching S_1 to the desired capacitor.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

RC AND RL FILTERS

APPLICATIONS OF NETWORKS

POWER SUPPLY FILTER

ATTENUATION EQUALIZERS

VARIABLE EQUALIZERS

51. Draw a T-type RC low-pass filter and a π -type RC high-pass filter.

52. In the circuit of Figure 27, R_1 , C_1 and C_2 form a (a) low-pass filter, (b) high-pass filter.

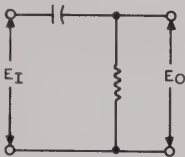
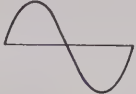
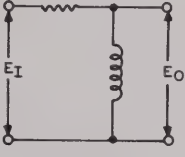
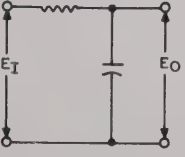
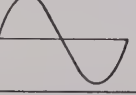
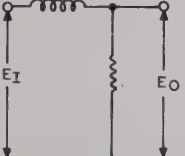
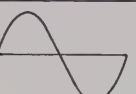
53. For minimum ripple in the output of the power supply of Figure 27, R_1 and C_2 should have a (a) short time constant, (b) long time constant.

54. What is the purpose of an attenuation equalizer?
55. In the circuit of Figure 29 at frequencies below f_c , is X_L greater than R ?
56. When the slider on R_2 is moved upward in the circuit of Figure 31A, the high-frequency attenuation is (a) increased, (b) decreased.
57. The circuit of Figure 31B is basically a (a) high-pass, (b) low-pass filter.

SUMMARY

In this lesson we have considered the effects of RC and RL networks. Depending on the arrangement of the components and the time constant of the network, a given RC or RL network has a certain effect on the amplitude, waveform and phase shift of a voltage applied to its input.

By making use of the network characteristics, the shape of the input voltage wave can be altered considerably. Also, networks can be used to attenuate certain ranges of frequencies, thus acting as filters, attenuators or equalizers. The characteristics of networks and the effects on sinewave and rectangular input voltages are summarized in the following chart.

NETWORK	DIAGRAM	E_I INPUT WAVEFORM	REQUIRED TIME CONSTANT FOR					
			SMALL CHANGE IN OUTPUT			LARGE CHANGE IN OUTPUT		
			AMPLITUDE (E_O)	WAVEFORM	PHASE SHIFT	AMPLITUDE (E_O)	WAVEFORM	PHASE SHIFT
HIGH-PASS RC			LONG	LONG		SHORT	SHORT	
			LONG		LONG	SHORT		SHORT
HIGH-PASS RL			LONG	LONG		SHORT	SHORT	
			LONG		LONG	SHORT		SHORT
LOW-PASS RC			SHORT	SHORT	SHORT	LONG	LONG	LONG
			SHORT		SHORT	LONG		LONG
LOW-PASS RL			SHORT	SHORT	SHORT	LONG	LONG	LONG
			SHORT		SHORT	LONG		LONG

IMPORTANT DEFINITIONS

ATTENUATION EQUALIZER — A network designed to attenuate frequencies which are causing undesired inequalities in response.

BAND-PASS FILTER — A filter that accepts all frequencies between two limits and attenuates all frequencies above and below these limits.

BAND-REJECTION FILTER — A filter that attenuates all frequencies between two limits and passes all frequencies above and below these limits.

CUTOFF FREQUENCY — That frequency at which a filter changes from rejection to pass.

FILTERS — Transmission networks designed to pass a specific range of frequencies and reject all others.

HIGH-PASS FILTER — A circuit which passes all frequencies above a certain frequency and attenuates all below.

HIGH-PASS NETWORK — A network in which the magnitude of the output increases with increasing sinewave voltage frequency.

LC NETWORK — An electric circuit containing inductance and capacitance.

LOW-PASS FILTER — A circuit which passes all frequencies below a certain frequency and attenuates all above.

LOW-PASS NETWORK — A network in which the magnitude of the output amplitude decreases with increasing sinewave voltage frequency.

L-SECTION FILTER — A filter network in which the series and shunt impedances take the shape of an inverted letter L.

MICROSECOND — A small unit of time equal to one millionth of a second.

PERIOD — (t) — The time interval of one cycle.

RESPONSE — The effect which a network or circuit has on a signal at a particular frequency or over a band of frequencies.

IMPORTANT DEFINITIONS (Continued)

SERIES IMPEDANCE — In an L-section filter, the component which is in series with one leg of the output circuit.

SHUNT IMPEDANCE — In an L-section filter, the component which is in parallel with the output circuit.

TIME CONSTANT — (T) — The time required for a quantity to change 63.2% of the total change that will occur. It is equal to the product of the capacitance in farads and the resistance in ohms for an RC circuit and the inductance in henries divided by the resistance in ohms for an RL circuit.

ESSENTIAL SYMBOLS AND EQUATIONS

C Capacitance (farads)

f Frequency (hertz)

L Inductance (henries)

R Resistance (ohms)

T Time constant (RC or RL) (seconds)

t — Period (seconds)

$$T = L/R \quad (1)$$

$$T = RC \quad (2)$$

$$t = \frac{1}{f} \quad (3)$$

PRACTICE EXERCISE SOLUTIONS

1. A microsecond is equal to one one-millionth of a second (1×10^{-6} sec).
2. In an inductive circuit, voltage leads current.
3. The current changes by 63.2% in one time constant.
4. Five time constants are considered sufficient for a full change of current in an RL circuit.
5. At the end of 3 time constants, the current has changed 95% from its original value.
6. The time constant of an RL circuit is $T = L/R$.
7. The maximum circuit current is equal to $150V/50\Omega$ or 3 amperes. The circuit current will reach this value in approximately 5 L/R time constants. The value of one time constant is $10/50$ or .2 seconds. The current will reach maximum in 5 time constants, $5 \times .2$ or 1 second.
8. The time constant is inversely proportional to the value of R. Thus, increasing the value of R decreases the length of the time constant.
9. When the switch is opened, the magnetic field collapses, inducing a voltage into the coil. The coil acts like a source and current flows through R, as shown in Figure 5B. The voltage developed across the inductor decreases exponentially so that at the end of 5 time constants, the induced voltage is essentially zero.
10. False — The time constant is inversely proportional to the value of R. Thus, decreasing the value of R increases the length of the time constant.
11. In a capacitive circuit, voltage lags current.
12. When the switch is closed, the circuit current is maximum and the voltage drop across the capacitor is zero.
13. Five time constants are required for a capacitor to become fully charged or to fully discharge.
14. The formula for the time constant of an RC circuit is $T = RC$.
15. The time constant of the circuit is $T = RC = 1 \times 10^5 \times .15 \times 10^{-6} = .15 \times 10^{-1}$ or .015 seconds. Since five time constants are required for full charge, the capacitor will reach full charge in $5 \times .015$ or .075 seconds.

PRACTICE EXERCISE SOLUTIONS (Continued)

16. During the first instant of charge, all of the source voltage appears across the resistor and the capacitor voltage is zero. As the capacitor charges, the voltage across the resistor decreases. At the end of five RC time constants the capacitor voltage is equal to the source voltage and the voltage drop across the resistor is zero.
17. Yes — The sum of the voltage drops across the resistor and capacitor always equals the source voltage.
18. The RC time is directly proportional to the value of R. Thus, increasing the value of R increases the length of the time constant.
19. Nothing — The value of source voltage has no effect on the RC time constant.
20. During discharge, the resistor and capacitor are in parallel and thus their voltages are equal. The voltage across the resistor and capacitor decreases exponentially for five time constants as shown by curve 2 in Figure 3.
21. Referring to the chart of Figure 9, the capacitor voltage after 3 time constants is 5% of the maximum. Thus, the capacitor voltage is 5% of 250 volts or 12.5 volts. The value of one time constant is 1×10^4 ohms $\times .25 \times 10^{-6}$ farads = $.25 \times 10^{-2}$ or .0025 seconds. Since five time constants are required for total discharge, the discharge time is $5 \times .0025$ or .0125 seconds.
22. The two batteries in Figure 10 provide a rectangular voltage waveform when switch S is periodically moved back and forth. Due to the resistance in the circuit, it takes some time for the capacitor to charge and discharge. As a result, the rise and decay of voltage across the capacitor follows the exponential shape of Figure 11A. The voltage across the resistor is proportional to circuit current. Since current is maximum at the first instant of charge and discharge, the voltage across the resistor is initially maximum each time the supply voltage changes, and then decreases exponentially, as shown in Figure 11B.
23. At the instant the source voltage reverses polarity, the voltage across the capacitor and the source voltage are series aiding. As a result, the resistor voltage is twice the source voltage.
24. B, A — In an inductive circuit, current increases exponentially so that the voltage across the resistor follows the waveform of Figure 11A. The voltage across the inductor follows the waveform of Figure 11B since the induced emf is maximum when the source is charging at its greatest rate.

PRACTICE EXERCISE SOLUTIONS (Continued)

25. When the source changes polarity, the induced emf aids the source voltage, developing a voltage across the inductor which is equal to the sum of the induced voltage plus the source voltage.
26. The peaked waveform can be obtained across the resistor in an RC circuit and across the inductor in an RL circuit.
27. The period is found by employing Equation 3:

$$t = \frac{1}{f} = \frac{1}{1 \times 10^3} = 1 \times 10^{-3} \text{ or } .001 \text{ second.}$$

28. A short time constant is no more than one tenth the period of the applied voltage and a long time constant is at least 10 times the period of the applied voltage.
29. The time constant is short with respect to the period:

$$\begin{aligned} T &= RC = 1 \times 10^3 \times .01 \times 10^{-6} \\ &= .01 \times 10^{-3} \text{ or } 1 \times 10^{-5} \text{ seconds.} \end{aligned}$$

$$t = 1/f = 1/1 \times 10^3 = 1 \times 10^{-3}.$$

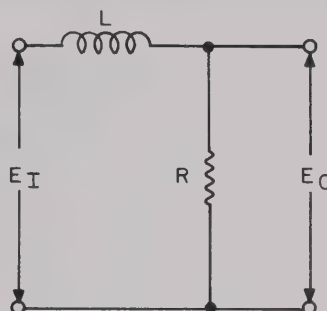
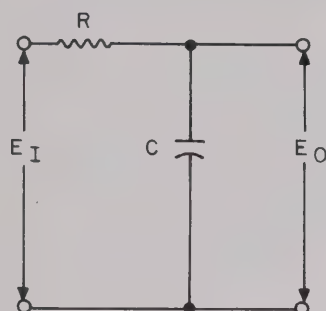
The time constant is therefore $1 \times 10^{-5} \div 1 \times 10^{-3} = 1 \times 10^{-2}$ or 1/100 of the period.

30. A high-pass network provides a greater output for high-frequency components of a signal while a low-pass filter provides a greater output for low-frequency components.
31. (b) short. — With a short time constant, the capacitor will charge quickly, developing the peaked waveshape across the resistor. With a long time constant, the capacitor will not charge much, and the voltage developed across the resistor will resemble the input waveshape.
32. A peaked waveform is developed across the inductor in an RL circuit when the time constant is short with respect to the period.
33. (a) long. — With a long time constant the effects of stored energy are reduced and the waveshape is not appreciably affected.
34. No — The waveshape is not affected. Only the amplitude and phase shift is altered when a sinewave is passed through a high-pass filter.
35. (a) long — With a short time constant the output amplitude is minimum.

PRACTICE EXERCISE SOLUTIONS (Continued)

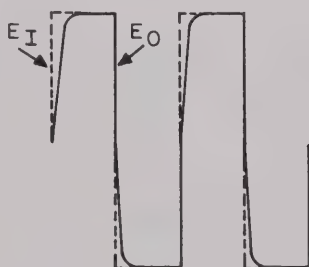
36. (a) leads the input signal. — In a high-pass network, the output signal always leads the input signal. The lead angle depends upon the time constant. A short time constant produces a large lead angle and vice versa.

37.



38. The output signal has a triangular waveshape, as shown in Figure 21C.

39. The output waveshape is close to a rectangular shape, since the time constant ($T = RC = 1 \times 10^3 \times .1 \times 10^{-6} = .0001$ second) is short with respect to the period ($t = 1/f = 1/10^2 = .01$ second).

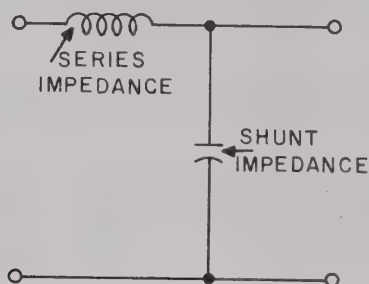


40. (b) short. — With a long time constant, the output amplitude will be minimum.
41. The output signal lags the input signal in a low-pass filter with a sinewave input.
42. A filter is a transmission network that passes alternating current signals within a given band of frequencies while reducing the amplitude of signals outside the desired band of frequencies.
43. The output voltage is maximum at resonance and also when the component across which the output is taken has a high reactance with respect to the reactance of the other component.

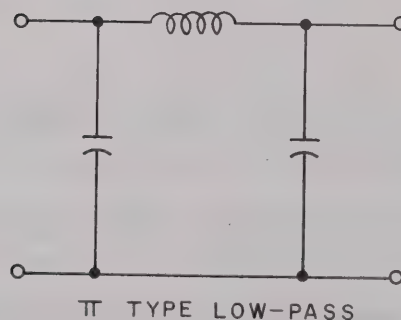
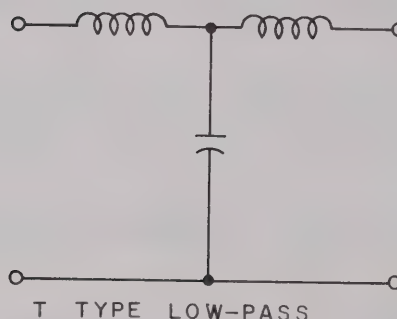
PRACTICE EXERCISE SOLUTIONS (Continued)

44. A band-pass filter passes all frequencies between certain limits while attenuating all others. Conversely, a band-rejection filter attenuates all frequencies between certain limits while freely passing all others.
45. You would use a low-pass filter since it passes all signal frequencies below a certain limit while attenuating all above the limit.

46.



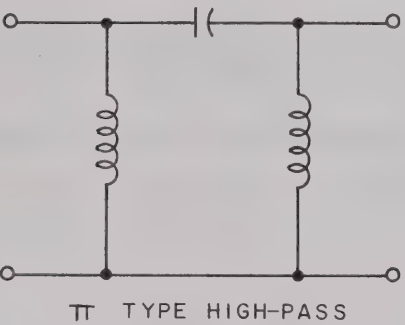
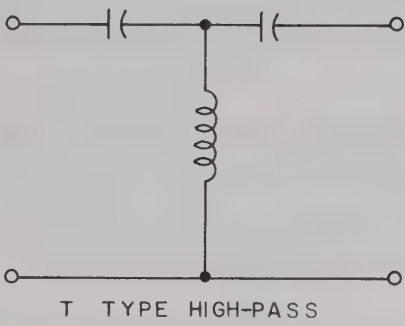
47.



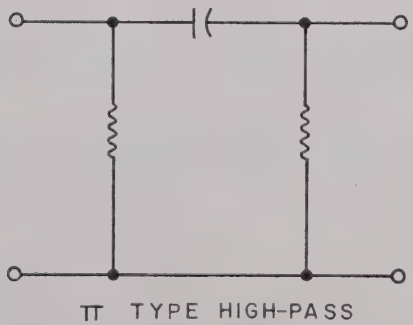
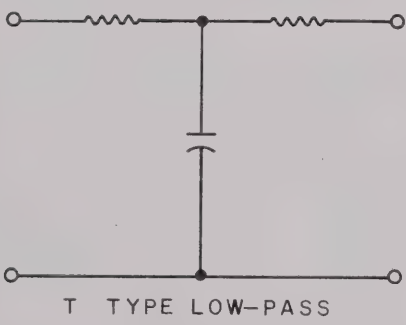
48. The cutoff frequency in a low-pass filter is the frequency below which the desired transmission is obtained and above which the signals are attenuated.
49. Below the cutoff frequency, X_L is less than X_C so that minimum attenuation is obtained.

PRACTICE EXERCISE SOLUTIONS (Continued)

50.



51.



PRACTICE EXERCISE SOLUTIONS—(Continued)

52. (a) low-pass filter. — A power supply filter is a low-pass filter since it must pass the low frequencies (dc) and attenuate the high frequencies (ripple).
53. (b) long time constant. — With a short time constant, the ripple would appear in the output. The longer the time constant, the lower the ripple.
54. An attenuation equalizer is used to compensate for the unequal attenuation characteristics of the transmission network.
55. No — Below f_c , X_C is greater than R and X_L is less than R . Above f_c , X_C is less than R and X_L is greater than R .
56. (a) increased. — Moving the slider upward decreases the value of R_2 , thereby increasing the effectiveness of C_1 .
57. (a) high-pass — Since the output is taken across the resistor, the circuit is a high-pass filter.

10-3

1001

25x10⁴ x 5 10⁸
10125

2.4
2.4
100
2.5x10⁴ x 5 10⁸
2.5
2.5
2.5



ONE OF THE

BELL & HOWELL SCHOOLS

1070A,B&C
EXAMINATION
CHECK SHEET

NOTICE: To keep our lessons up-to-date, we add material to the texts from time to time, and make occasional changes in the examination questions. Therefore, when checking your answers with this check sheet, look at the code LETTER (A, B, C, etc.) on your examination sheet to determine which of the following groups of answers apply to the lesson which you have.

1070C

1. C - WITHIN FIXED INTERVALS OF TIME, THE TIME CONSTANT OF A CIRCUIT IS -- THE RECURRING 63.2% RISE OR FALL OF CURRENT.

The length of a time constant is dependent upon the values of the circuit components.

2. D - FOR FIGURE 1B, IF THE INDUCTANCE L IS 2.4 HENRIES, AND RESISTANCE R IS 300 OHMS; THE TIME CONSTANT OF THE CIRCUIT IS -- .008 SECONDS.

The time constant of an LR circuit is found using Equation 1:

$$T = L/R = 2.4/3 \times 10^2 = .8 \times 10^{-2} \text{ or } .008 \text{ second.}$$

3. C - AN RC CIRCUIT CONTAINS A RESISTOR OF 250,000 OHMS AND A CAPACITOR OF .05 MICROFARAD CONNECTED TO A VOLTAGE SOURCE OF 100 VOLTS. THE TIME CONSTANT IS -- .0125 SECOND.

The time constant of an RC circuit is found using Equation 2:

$$T = RC = 2.5 \times 10^5 \times .05 \times 10^{-6} = 2.5 \times 10^5 \times 5 \times 10^{-8} = 12.5 \times 10^{-3} \text{ or } .0125 \text{ second.}$$

4. B - IF THE FREQUENCY OF THE VOLTAGE SOURCE IN QUESTION 3 IS 1 kHz, THE CIRCUIT TIME CONSTANT IS -- LONG WITH RESPECT TO THE PERIOD.

The period of the 1 kHz voltage source is $1/1 \times 10^3 = 1 \times 10^{-3}$ or .001 second. Since the time constant is .0125 second, the time constant is twelve and one half times the period.

5. D - FOR RL AND RC CIRCUITS, THE CHANGE IN OUTPUT WAVEFORM DEPENDS UPON -- THE TIME CONSTANT OF THE CIRCUIT AND THE FREQUENCY OF THE INPUT SIGNAL.

The ratio of period (period = $1/f$) to time constant determines the output signal waveshape.

6. A - A HIGH-PASS NETWORK -- PROVIDES GREATER OUTPUT FOR THE HIGH-FREQUENCY COMPONENTS.

The high-pass filter attenuates the low-frequency components and passes the high-frequency components.

7. B - IN A HIGH-PASS RC NETWORK FOR SINEWAVES, TO ALLOW ONLY A SMALL CHANGE IN THE OUTPUT VOLTAGE AMPLITUDE, THE TIME CONSTANT IS -- LONG.

With a short time constant the output amplitude will be greatly reduced and will lead the input.

8. A - IN A HIGH-PASS RC NETWORK FOR RECTANGULAR INPUT VOLTAGES, TO ALLOW A LARGE CHANGE IN OUTPUT VOLTAGE AND WAVEFORM, THE TIME CONSTANT IS -- SHORT.

With a short time constant a peaked output waveform will result.

9. D - FOR MAXIMUM OUTPUT IN THE CIRCUIT OF FIGURE 23A, -- X_C MUST BE GREATER THAN X_L . For maximum output, the series impedance X_L must be less than the shunt impedance X_C .

10. C - IF R_1 AND C_2 IN FIGURE 27 HAVE A SHORTER THAN NORMAL TIME CONSTANT, -- THE RIPPLE VOLTAGE INCREASES.

To provide good filtering action with low ripple voltage, the time constant must be long.

1070B

All explanations are the same as for 1070C except for those given below.

2. D - FOR FIGURE 2, IF THE INDUCTANCE L IS 2.4 HENRIES, AND RESISTANCE R IS 300 OHMS; THE TIME CONSTANT OF THE CIRCUIT IS -- .008 SECONDS.

The time constant of an LR circuit is found using Equation 1:

$$T = L/R = 2.4/3 \times 10^2 = .8 \times 10^{-2} \text{ or } .008 \text{ second.}$$

9. D - FOR MAXIMUM OUTPUT IN THE CIRCUIT OF FIGURE 21A, -- X_C MUST BE GREATER THAN X_L . For maximum output, the series impedance X_L must be less than the shunt impedance X_C .

1070A,B & C

EXPERIMENT 4

RC TIME CONSTANTS

PARTS NEEDED

- | | |
|--|--|
| 1 - Complete Design Console | 1 - 10 k Ω , 1/2 W, 20% Resistor |
| 1 - Multimeter with Test Leads and Spring Adapters | 1 - 1000 μ F, 50 Volt Electrolytic Capacitor |
| 1 - 470 Ω , 1/2 W, 20% Resistor | 5 - Modular Connectors |
| 1 - 2.2 k Ω , 1/2 W, 5% Resistor | - No. 22 Solid Hookup Wire |

OBJECTIVE

The time constant of a series RC circuit is equal to the product of R and C. At the end of one time constant interval, the capacitor charges to 63% of the available source dc voltage. Thus, at the end of one time constant, the capacitor voltage is 63% of the source; at the end of the second time constant period, the capacitor voltage is 86% of the source, and so on. In this experiment, you will examine the time constant action in an RC circuit and compare measured and calculated results.

PROCEDURE

1. Set up the circuit shown in Figure 4-1 following the layout of Figure 4-2 (be sure to observe the capacitor polarity). The jumper wire marked X is used to discharge the capacitor through the 470 Ω resistor. Because of the high value of C_1 , it should not be discharged with a short. The jumper wire marked Y is used as a switch to apply voltage to the RC circuit (when jumper X is removed).
2. Be sure that both jumpers X and Y are NOT in the circuit. Turn on the design console, set the low voltage power supply to the 30 volt range and rotate the ADJUST VOLTAGE control for a 30 volt output.
3. Calculate the RC time constant of the circuit of Figure 4-1.
Time Constant = $R_1 \times C_1 =$ 10 ^{$\times 10^{-3}$} seconds
4. Place your watch or other time piece with a sweep second hand close to your meter so you can observe both simultaneously. Connect the multimeter to measure the voltage drop across C_1 . Pick a convenient starting time, and connect jumper wire Y into the circuit. Record the voltage across the capacitor at the end of each 10 second interval in the E_{C_1} column in the chart of Figure 4-3 (at the instant that the jumper is connected, TIME = 0 SEC). You might repeat the process several times to check your results. Before each new run, disconnect jumper Y and connect jumper X into the circuit for at least 5 seconds to discharge the capacitor. Be sure to remove jumper X before each

measurement run.

Note: Because of the loading effects of the meter, the capacitor voltage will not quite reach the supply voltage. Typically, after 5 time constants, the capacitor voltage will be equal to about 29 volts when the source voltage is 30 volts.

5. Repeat the process described in Step 4, but instead measure the voltage drops across R_1 and record the values in the E_{R_1} column in the chart of Figure 4-3. Repeat the process several times to verify your results.

At the time equal to zero (the instant that the jumper Y is placed into the circuit) the voltage across the resistor will be the source voltage. The meter pointer will not react quickly enough to show this, and thus it is entered in the chart of Figure 4-3.

6. Using the data recorded in Figure 4-3, plot the curves for E_{C_1} and for E_{R_1} on the graph of Figure 4-4. Label each curve. Your two curves should have the general appearance of those shown in Figure 4-5.

7. Let's see how your measured results compare to the theory of RC circuits. At the end of each time constant, the capacitor voltage will be 63% of the available source voltage. Remember, the available source voltage is the difference between the source voltage and the capacitor voltage. Thus, for the 5 time constants, the capacitor voltage will be a percentage of the source voltage, as shown below.

TIME CONSTANT	CAP VOLTAGE AS % OF SUPPLY
1	63%
2	86%
3	95%
4	98%
5	100% (approx.)

8. Calculate the capacitor voltage for each of the time constants and record at the top of the next page. Remember, the supply voltage is 30 volts.

RC Time Constants

1st TIME CONSTANT (10 SEC) = 18.9 volts
2nd TIME CONSTANT (20 SEC) = 25.8 volts
3rd TIME CONSTANT (30 SEC) = 28.5 volts
4th TIME CONSTANT (40 SEC) = 29.4 volts
5th TIME CONSTANT (50 SEC) = 30.0 Volts

9. Compare the calculated values of Step 8 to those measured in Step 4. They should compare favorably. Differences are due to the tolerances of R_1 and C_1 , as well as the effects of the loading of the meter on the circuit.

10. The time constant is directly proportional to the product of R and C , as mentioned earlier. To illustrate this fact, replace R_1 in the circuit of Figure 4-6 with a $2.2\text{ k}\Omega$ resistor.

$$RC = 2.2 \times 10^3 \times 10^{-6}$$

Following the general procedure described in Steps 4 and 5, complete the chart of Figure 4-6. With the lower value of R_1 , the time constant is reduced, and thus the voltage changes occur in a shorter period of time. It may be necessary to take a reading, record it, remove jumper Y, discharge the capacitor with jumper X, remove jumper X, replace jumper Y and time from zero seconds to the next time shown in the chart.

11. Plot the curves for E_{C_1} and E_{R_1} on the graph of Figure 4-7, using the data in the chart of Figure 4-6. Note that, although the time scale is different, the curves have the same shape as in Figure 4-4.

CONCLUSION

In a series RC circuit, the time constant is equal to the product of R and C . When a constant dc voltage is applied to such an RC circuit, the voltage across the capacitor increases; and the voltage across the resistor decreases until the capacitor charges to the source voltage. The charging action, as a rule-of-thumb, takes 5 time constants. At the end of each time constant interval, the capacitor charges to 63% of the available source voltage.

NOTES

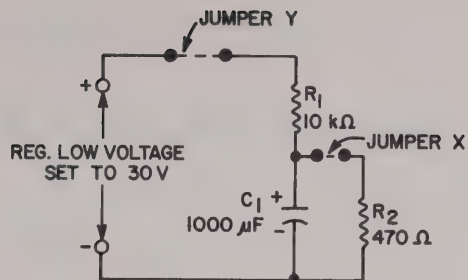


FIGURE 4-1

TIME (SEC)	E_{C_1}	E_{R_1}
0	0 V	30 V
10	17	14
20	23	7
30	26	4
40	27	3
50	28	2
60	29	1

FIGURE 4-3

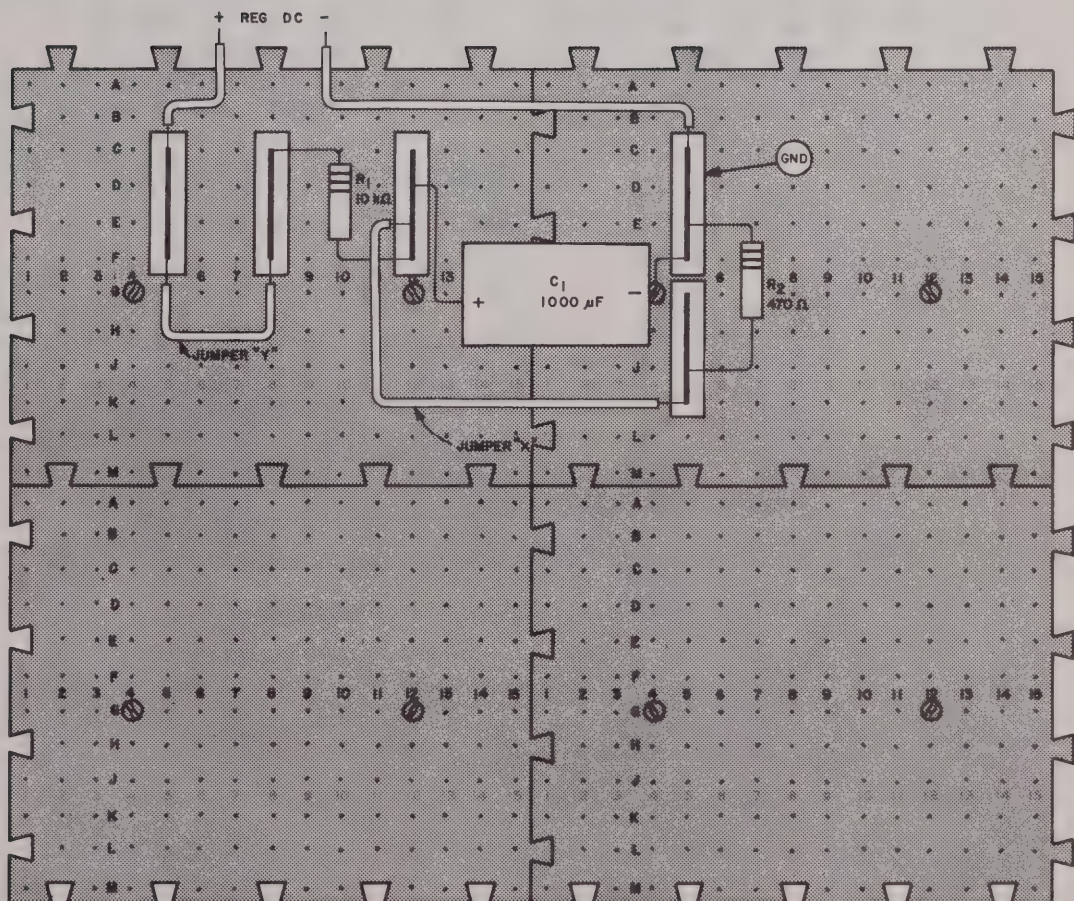


FIGURE 4-2

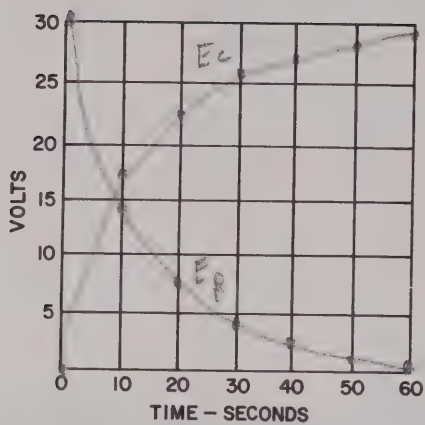


FIGURE 4-4

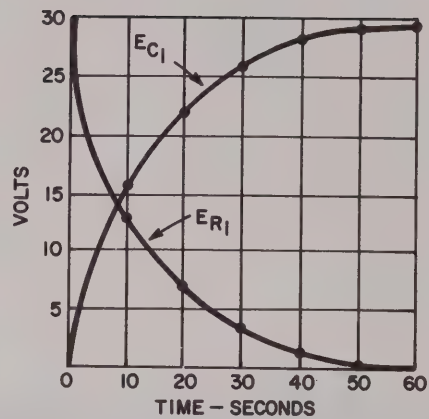


FIGURE 4-5

TIME (SEC)	E_{C1}	E_{R1}
0	0 V	30 V
2	10	20
4	20	10
6	26	4
8	28	2
10	29	1
12	29	1

FIGURE 4-6

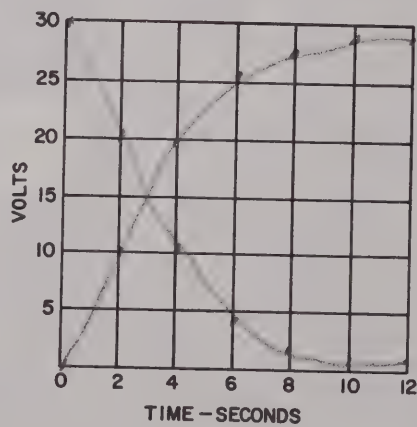


FIGURE 4-7



ONE OF THE

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9506-4A
EXAMINATION
CHECK SHEET

1. C - WHAT IS THE TIME CONSTANT IN A SERIES RC CIRCUIT IF $R = 150 \text{ k}\Omega$ AND $C = 10 \text{ }\mu\text{F}$?
-- 1.5 SEC.

The time constant is equal to the product of R and C:

$$T = R \times C = 150 \text{ k}\Omega \times 10 \text{ }\mu\text{F} = .15 \times 10^6 \times 10 \times 10^{-6} = 1.5 \text{ sec.}$$

2. D - TO WHAT PERCENTAGE OF THE AVAILABLE SOURCE VOLTAGE DOES A CAPACITOR CHARGE DURING EACH TIME CONSTANT? -- 63%.
During each time constant the capacitor charges to 63% of the available source voltage, which is the difference between the capacitor voltage and the supply voltage.

3. A - AN RC CIRCUIT CONSISTING OF A $20 \text{ }\mu\text{F}$ CAPACITOR AND A $250 \text{ k}\Omega$ RESISTOR IS CONNECTED TO A 100 VOLT SOURCE. WHAT IS THE VOLTAGE ACROSS THE CAPACITOR AT THE END OF 10 SECONDS? -- 86 VOLTS.

The time constant of this circuit is $T = R \times C = .25 \times 10^6 \times 20 \times 10^{-6} = 5 \text{ sec.}$ Thus, at the end of 10 seconds or 2 time constants, the capacitor voltage will be 86 volts.

4. B - REFERRING TO THE CIRCUIT DESCRIBED IN QUESTION 3, WHAT IS THE VOLTAGE ACROSS THE RESISTOR AT THE END OF 5 SECONDS? -- 37 VOLTS.

At the end of the first time constant, the capacitor voltage is 63 volts; and the resistor voltage is $100 - 63$ or 37 volts.

5. C - WHAT HAPPENS TO THE TIME CONSTANT IN AN RC CIRCUIT IF THE VALUE OF RESISTANCE IS DOUBLED AND THE VALUE OF CAPACITANCE IS HALVED? -- REMAINS THE SAME.

Doubling the value of resistance and halving the value of capacitance would keep the time constant the same as shown below:

$$T = 2RC/2 = RC.$$

RADIO FREQUENCY EFFECTS

1073



The properties of the components used in the high frequency circuits of a television receiver are very critical. These components must be carefully selected to provide a good picture.

Courtesy Zenith Radio Corp.

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*The only hopeless failure is the person who
has ceased to strive for success.*

—Selected

RADIO FREQUENCY EFFECTS

We generally think of **RADIO FREQUENCIES** as those frequencies between 10^4 hertz (cycles per second) and 10^{11} hertz. The circuits used for radio frequency voltages and currents differ considerably from those used for lower frequency voltages and currents. Many effects that are not present in dc circuits and go unnoticed at lower frequencies become very pronounced at radio frequencies.

Resistance, capacitive reactance and inductive reactance of a circuit vary considerably with changes in frequency. Effects such as stray capacitance, stray inductance and skin effect which do not affect low frequency or dc circuits have considerable effect on radio frequency circuits. For example, it is not uncommon to have a stray capacitance of 10 picofarads (10×10^{-12} farads) between two wires in a circuit. At a low frequency of 100 hertz a stray capacitance of 10 picofarads has a reactance of about 160 megohms. However, at a radio frequency of 100 megahertz the reactance is only about 160 ohms. This stray capacitance offers a low reactance path at radio frequencies which would not have to be considered at lower frequencies.

Like low frequency and dc energy, radio frequency energy can be transmitted from one point to another by means of wire conductors. However, unlike low frequency and dc energy, radio frequency energy can be transmitted through space without wire conductors in the form of **ELECTRO-MAGNETIC WAVES**. This phenomenon makes radio and television transmission possible.

Radio frequency currents and radio frequency electromagnetic energy are used for many purposes other than radio and television transmission. Radar systems use r-f energy to locate and track aircraft, missiles and satellites. Many industries use r-f energy to heat metals, plastics and other materials. Doctors use r-f energy for many types of medical therapy. Every day, engineers and technicians discover many new applications for r-f energy.

CIRCUIT COMPONENTS AT RADIO FREQUENCIES

Like low frequency circuits, radio frequency circuits are made up of conductors, resistors, inductors, capacitors, and tubes or transistors. However, as previously mentioned, many effects that are not present in dc circuits and go unnoticed at lower frequencies become very pronounced at radio frequencies.

Keep in mind that circuit properties are different from circuit components. For example, an inductor is a circuit component and inductance is a circuit property. An inductor may have considerable resistance and stray capacitance as well as inductance. In fact, each circuit component has some resistive, inductive and capacitive properties. Some of the properties are unimportant in low frequency circuits but have considerable effect on radio frequency circuits.

Conductors

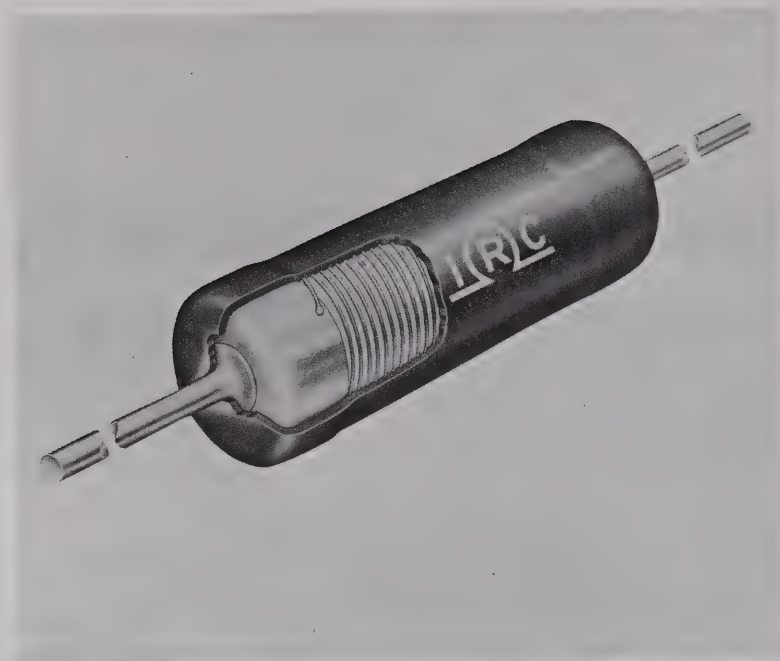
An r-f current in a conductor produces a changing magnetic field around the conductor. While the field is building up and collapsing, the flux lines cut the conductor. This action induces a counter emf which opposes the current in the conductor. This opposition is called inductive reactance.

Since inductive reactance is directly proportional to frequency, a conductor may have a negligible inductive reactance at low frequencies and a very large inductive reactance at radio frequencies. As an example, the leads of resistors and capacitors and the internal leads of vacuum tubes have considerable inductive reactance at radio frequencies. Thus, a careful choice of circuit components and a proper circuit layout is needed to keep conductors as short as possible in r-f circuits.

With an alternating current in a conductor, the magnetic flux lines originate at the center of the conductor and expand outward. They are more concentrated at the center than near the surface of the conductor, and thus the counter emf is greater at the center of the conductor than at the surface. The result of this action is that current tends to concentrate along the surface of the conductor, and the effective cross-sectional area is reduced. Since the resistance of a conductor is inversely proportional to its cross-sectional area, the resistance of a conductor increases at very high frequencies. This effect is called SKIN EFFECT.

A conductor may have a resistance of only a fraction of an ohm for direct current. This resistance is referred to as the dc resistance. However, at radio frequencies the same conductor may have a resistance equal to many times the dc resistance. This difference in the resistance of the conductor is a result of the skin effect.

For radio frequencies up to about 2 megahertz, the skin effect may be reduced by using litz conductors. A litz conductor is made up of a number of small diameter, interwoven, separately insulated strands of wire. Since current can pass along the surface of the small wires, a litz conductor has a much larger effective surface area than a solid conductor of equal diameter.



Wirewound resistors like the one shown above can exhibit inductive properties at high frequencies. This can be used to advantage where a combination inductor-resistor is needed in a circuit.

Courtesy IRC Division of TRW, Inc.

At frequencies above 2 megahertz, a litz conductor loses its effectiveness because of irregularities in the small wires and capacitance between the strands. For r-f currents above 2 megahertz, large diameter tubing is often used as a conductor to keep the skin effect to a minimum. The conductors which carry large r-f currents in radio transmitters are often an inch or more in diameter. Also, since the r-f currents only travel along the surface of the conductor, the conductors are plated with a low resistance metal such as silver to increase the surface conductivity and reduce the ac resistance.

Resistors

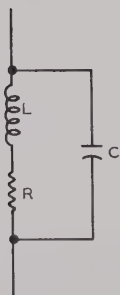


Figure 1

Figure 1 is an equivalent circuit of a resistor for radio frequencies. Notice that the resistor has the properties of inductance L and capacitance C , as well as resistance R . The inductance L is due to the connecting leads or pigtailed at the resistor terminals and the resistance element itself. When used in an r-f circuit, the resistor leads must be kept as short as possible to obtain a low inductance. Also, since the inductance of a conductor is proportional to its length, resistors must be constructed with short resistance elements to have low inductances.

Wirewound resistors usually have much greater inductances than composition types. However, at times they must be used because of their greater power dissipation ratings. Sometimes special winding methods are used to wind wirewound resistors which reduce their inductance to a low value.

The windings resulting from these methods are called "non-inductive" windings.

Basically, a capacitor is made up of two conductors separated by a dielectric insulating material. The capacitance is directly proportional to the area of the conductor surface and inversely proportional to the distance between the conductors. Thus, any two conductive points separated by an insulator, however imperfect, have capacitance between them. Therefore, a resistor has capacitance between its two terminals which are separated by the resistance elements. One way to minimize the capacitance of a resistor is to use small diameter terminals to decrease the end area.

Referring to Figure 1, notice that the inductance L and capacitance C of a resistor form a parallel resonant circuit. At the resonant frequency the impedance of the resistor may be considerably higher than the resistance alone.

Capacitors

Figure 2 is an equivalent circuit of a capacitor. The resistance R is due to the resistance of the capacitor plates and the connecting leads, or pigtails, and the resistance effects of the dielectric. The resistance effects of the dielectric are called dielectric losses. Capacitors which use air or vacuum as a dielectric have the smallest dielectric losses. The inductance L is due to the inductance of the connecting leads and the plates of the capacitor. Notice that the inductance and capacitance form a series resonant circuit. When the applied signal frequency is below the resonant frequency of the capacitor, the capacitive reactance is greater than the inductive reactance. Thus, at low frequencies a capacitor may be represented as a resistance and capacitance in series. However, at frequencies above resonance the inductive reactance is greater than the capacitive reactance. The capacitor then acts like an inductance in series with a resistance. Tubular paper capacitors usually have a larger inductance than other types of capacitors.

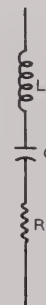


Figure
2

The leakage resistance of a capacitor may be represented as a resistance connected across the capacitor. However, the leakage resistance of all but electrolytic capacitors is usually so high that it can be neglected for most practical purposes.

Inductors

Basically, an inductor is made up of a conductor wound in the form of a coil to concentrate the magnetic field in a relatively small area and increase the

self inductance. An inductor can be represented by an equivalent circuit like that of a resistor, as shown in Figure 1. The values of L , C and R are, of course, much different for an inductor than for a resistor. The resistance of the inductor is due to the resistance of the conductor used to wind the inductor. The skin effect is especially important in an inductor since it causes the ac resistance of an inductor to be many times greater than the dc resistance.

The capacitance of the inductor is the result of the many small capacitances between the turns of the inductor. This capacitance is called **DISTRIBUTED CAPACITANCE** because it is distributed along the length of the inductor.

The inductance and distributed capacitance of an inductor form a parallel resonant circuit. Thus, at frequencies below resonance the capacitive reactance is larger than the inductive reactance, and the inductor acts like an inductance in series with a resistance. At frequencies above resonance the inductive reactance is greater than the capacitive reactance, and the inductor acts like a capacitance in parallel with a resistance.

As in any parallel resonant circuit, there is an increase in impedance at frequencies near resonance. Thus, a circuit may not operate properly if the signal frequency is near the resonant frequency of an inductor in the circuit. To avoid this problem, various coil winding methods have been developed to reduce the distributed capacitance to a minimum. With a very small distributed capacitance, the resonant frequency of the inductor is far above the frequency of the applied signal. Under these conditions, the coil functions as an inductive reactance as desired.

In other applications requiring resonant circuits, the resonant circuit may be made up of an inductor and its distributed capacitance. This not only eliminates the need to reduce the distributed capacitance of the inductor, but also permits a savings in size and cost since only one component is required to make up a resonant circuit.

Resistance dissipates energy in the form of heat, while reactance returns its absorbed energy to the circuit without loss. Thus, in an inductor, the loss of energy is proportional to the effective resistance. The ratio of the reactance to the effective resistance of an inductor is an indication of the efficiency of the inductor. This ratio is referred to as the **QUALITY or Q** of the inductor. The higher the value of Q , the higher the efficiency of the inductor. In the form of an equation:

$$Q = \frac{X_L}{R} \quad (1)$$

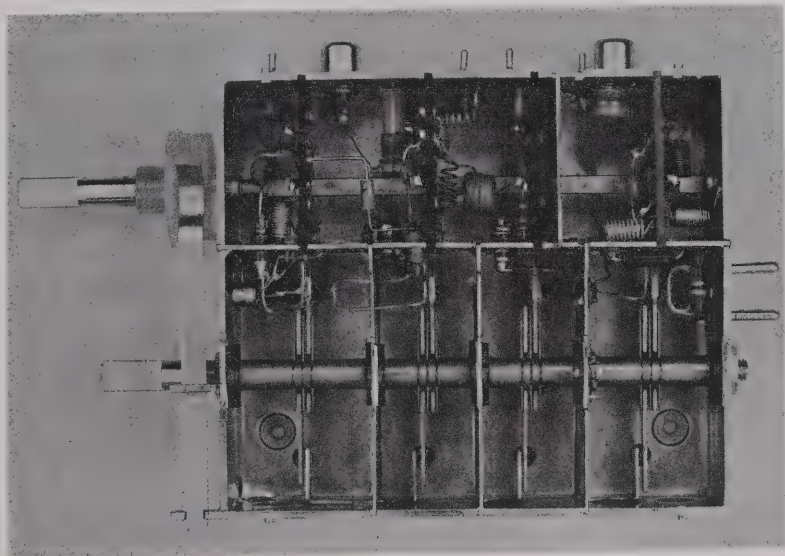
where Q is the quality,

X_L is the inductive reactance in ohms, and

R is the effective resistance in ohms.

This manner of expressing inductor efficiency is convenient because both the inductive reactance and the effective resistance increase with frequency. Thus, the Q may be fairly constant over the range of frequencies for which the inductor is designed to operate.

For many applications it is desirable that the Q of an inductor be as high as possible. This can be done by constructing the inductor so that the inductance is large in relation to the resistance. The inductance can be increased by using special types of windings and iron cores. The effective resistance of an inductor can be reduced by the same methods used to reduce skin effect in a conductor. That is, the effective resistance of an inductor can be reduced by using litz conductors, large diameter conductors, and by silver plating the conductors.



A UHF television tuner like the one shown above makes use of both lumped and distributed constants in the tuned circuits.

Courtesy Oak Manufacturing Co.

Distributed Constants

In many radio frequency circuits the inductance, capacitance, and resistance may not be LUMPED in individual components but instead may be DIS-

TRIBUTED over a large area like the distributed capacitance of an inductor. The resistance, capacitance and inductance of a circuit are known as constants, as opposed to variables such as the instantaneous values of a signal current and voltage. If the resistance, capacitance and inductance are lumped in individual components they are called LUMPED CONSTANTS, whereas if they are distributed over a larger area they are called DISTRIBUTED CONSTANTS.

One type of circuit in which the circuit constants are distributed instead of lumped in individual components is the transmission line. Transmission lines are used to transmit electric energy from a source to a load such as from a transmitter to an antenna.

One of the simplest forms of transmission line is made up of two conductors separated by spacers to maintain a constant spacing between them. Two parallel conductors like this have a certain capacitance and inductance per unit length. If this capacitance is 1 picofarad per inch, for example, a 10 inch length of this type of transmission line has a capacitance of 10 picofarads. Since a transmission line has inductance as well as capacitance, a length of transmission line can be used as a resonant circuit.

Two important advantages of using transmission lines or distributed constants instead of lumped constants for resonant circuits are: (1) it is much easier to obtain the required small values of inductance and capacitance for very high resonant frequencies and (2) resonant transmission lines have much higher values of Q than can be obtained with lumped constants.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

CIRCUIT COMPONENTS AT RADIO FREQUENCIES

CONDUCTORS

RESISTORS

CAPACITORS

INDUCTORS

DISTRIBUTED CONSTANTS

1. It is desirable to keep all connecting leads as short as possible in r-f circuits. True or False?
2. Due to the skin effect, radio frequency currents tend to concentrate (a) in the center of a conductor, (b) along the surface of a conductor.
3. Which is greater, the dc resistance or the ac resistance of a conductor?
4. Name two types of conductors used in r-f equipment to keep the skin effect to a minimum.
5. In r-f circuits, wirewound resistors are preferred over composition types. True or False?
6. At what frequency is the impedance of a resistor greater than the dc resistance?
7. Under what condition does a capacitor act like an inductance in series with a resistance?
8. What would be the disadvantage of using tubular paper capacitors in r-f circuits?
9. What is the source of the distributed capacitance of an inductor?
10. How should the natural resonant frequency of an inductor compare to the applied signal frequency to obtain the desired value of inductance in an r-f circuit?
11. Assume that you know from experience that a section of a radio receiver requires a parallel tuned circuit for proper operation. However in checking over a radio receiver of this type, you notice that there is no capacitor connected across the inductor in this section and yet this section of the receiver is operating properly. How can you account for this?

12. If an inductor has a reactance of 3000 ohms and an effective resistance of 100 ohms at a certain frequency, what is the **Q** of the inductor at this frequency?
13. How does the use of an iron core affect the **Q** of an inductor?
14. Give two advantages of using a section of a transmission line instead of lumped constants to form a resonant circuit at high radio frequencies.

THE ELECTROMAGNETIC SPECTRUM

Radio frequency electrical energy can be transmitted over wires like low frequency energy. Unlike low frequency energy, however, it is also practical to transmit radio frequency energy through space in the form of electromagnetic waves. Electromagnetic waves are a form of energy which propagates itself through free space at a speed of about 300,000,000 meters per second or 186,000 miles per second.

Radio waves, x-rays, and light waves are all forms of electromagnetic energy. The main difference in these forms of energy is their frequency. The chart

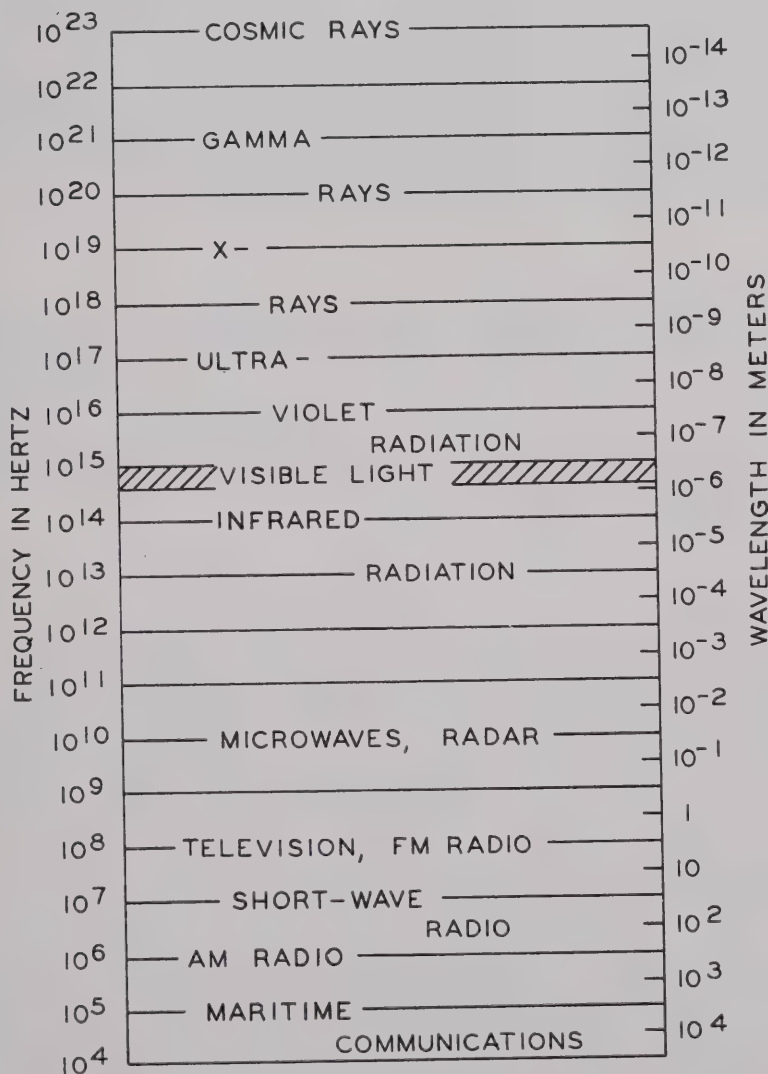


Figure 3

of Figure 3 shows the various classifications of electromagnetic energy according to frequency. The band of electromagnetic waves shown in Figure 3 is referred to as the known electromagnetic spectrum and covers the wide range of frequencies from 10^4 hertz to 10^{23} hertz.

The various classifications in Figure 3 represent bands of frequencies. For example, the commercial AM broadcast band extends from 535 kilohertz through 1605 kilohertz, and the complete television band extends from 54 megahertz through 890 megahertz. Various smaller bands are used for commercial FM radio and other services.

~~The lower frequency electromagnetic waves from the lower limit through microwaves are known as radio waves. They are generated most often by oscillating resonant circuits. The intermediate frequencies, from infrared to x-rays, are generated by the movement of molecules and by the movement of electrons within atoms and molecules. Gamma rays are generated by changes in the structure of atomic nuclei. Cosmic rays are produced in the conversion of matter to energy, as in a nuclear reactor, but there is much about this conversion which is unknown at present.~~

Although electronics is involved in the generation and control of all forms of electromagnetic energy, this lesson deals primarily with radio frequency electromagnetic energy. In the United States the use of the radio frequency spectrum is carefully controlled by the Federal Communications Commission (FCC). In Canada the Department of Transport (DOT) performs this function. Other countries have similar regulating agencies. Various international conventions and committees help prevent radio services of one country from interfering with those of another.

One of the main functions of the FCC is to allocate, or assign, frequencies for the various services including government, public safety, industrial, radio broadcasting, television broadcasting, navigation, amateur, and scientific and medical equipment. It is becoming increasingly difficult to provide these many services with adequate frequency bands within the available radio spectrum. However, increasing use of higher frequencies in the microwave region are easing this difficulty. Research indicates that even higher frequencies in the vicinity of light waves may be used in the near future for services now using radio waves.

WAVELENGTH

As shown in Figure 3, electromagnetic energy can also be classified according to **WAVELENGTH**. The wavelength of an electromagnetic wave is the dis-

tance traveled by an electromagnetic wave during the time of one cycle. This is equivalent to the distance between two corresponding points on neighboring cycles. For example, Figure 4 is a graph of two cycles of electromagnetic energy at some instant of time. Distance is plotted in a horizontal direction and intensity is plotted in a vertical direction.

At the instant of time shown in Figure 4, the positive peak of cycle 1 is at point B and the positive peak of cycle 2 is at point A. However, these waves are moving to the right at the speed of light so that one cycle of time later the positive peak of cycle 2 will reach point B. Thus, the distance from point A to point B is equal to one wavelength. The length of a wave in meters can be found by the following equation:

$$\lambda(m) = \frac{300,000,000}{f} \quad (2)$$

where f is the frequency in hertz, and

λ is the Greek letter lambda, with $\lambda(m)$ representing the wavelength in meters.

Wavelength can also be expressed in terms of feet since one meter is approximately 3.28 ft.

$$\lambda \text{ (ft.)} = \frac{984,000,000}{f} \quad (2a)$$

where f is the frequency in hertz, and

$\lambda \text{ (ft.)}$ is the wavelength in feet.

Notice that frequency and wavelength are inversely proportional. If frequency is doubled, wavelength is halved; if frequency is tripled, wavelength reduces to one-third; etc.

Referring to Equation 2, notice that a frequency of 1,000,000 hertz, near the center of the AM broadcast band, has a wavelength of 300 meters. A frequency of 100,000,000 hertz, near the center of the FM broadcast radio band, has a wavelength of 3 meters. Since the wavelength determines the length of the antenna required to efficiently transmit or receive an electromagnetic wave, FM broadcasts can be efficiently transmitted and received with much shorter antennas than AM broadcasts. Note, this is due only to the differences in frequency, and is not dependent upon the characteristics of

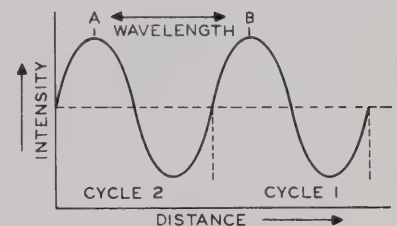


Figure
4

AM or FM transmission. Also, the various radio frequency effects, such as skin effect, distributed capacitance, and lead inductance described previously, are much more pronounced in FM radio circuits than in AM radio circuits. Thus, the component layout and wiring is much more critical in an FM receiver due to the frequencies involved and not due to the type of transmission.

PROPAGATION OF RADIO WAVES

When an r-f voltage is applied to a transmitting antenna, radio waves of the same frequency are radiated away from the antenna in much the same way that waves travel away from a disturbance on the surface of a pond. These radio frequency radiations are a type of electromagnetic wave. Electromagnetic waves are made up of electric and magnetic fields at right angles to each other and at right angles to the direction of propagation or motion. Figure 5 shows a number of instantaneous cross sections of a radio wave being radiated from a transmitter antenna. The dashed lines represent the magnetic flux lines, and the short, solid lines at right angles to the dashed lines represent the electric lines of force. As shown in Figure 5, the directions of the electric and magnetic fields reverse with each alternation of the r-f voltage applied to the antenna.

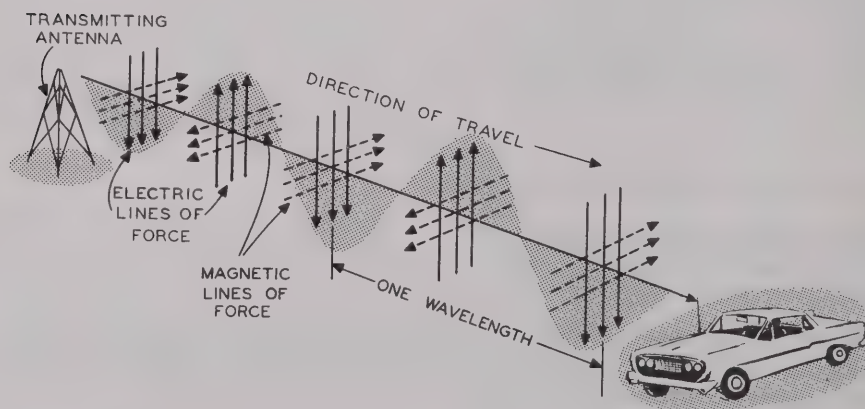


Figure 5

The propagation of the electromagnetic field depends on the fact that a moving electric field produces a magnetic field and, conversely, a moving magnetic field produces an electric field. Thus, an electric field creates a new magnetic field, which in turn creates a new electric field, and so on. The created field is produced a little beyond the parent field, so that the electromagnetic wave propagates itself through space at the speed of light,

about 300,000,000 meters per second or 186,000 miles per second in a vacuum. The difference between the speed of light in a vacuum and in air is negligible for most practical purposes.

The Dipole Antenna

To radiate radio waves efficiently we must use a properly designed antenna. Figure 6 shows the operation of a common type of antenna known as a **DIPOLE**. The antenna is made up of a length of wire cut in half and connected to the terminals of an r-f generator which represents the output of a transmitter. The length of the dipole and the frequency of the generator are selected so that the length of each half of the wire is one-quarter of the wavelength ($\lambda/4$) of the generator frequency. The total length of the antenna is one-half wavelength, and the antenna is called a half-wave dipole.

The electric and magnetic fields around the antenna are continually changing, but there are several points in the cycle at which we can easily determine their direction and relative magnitude.

In Figure 6A, the right terminal of the generator is at its maximum positive value and the left terminal is at its maximum negative value. The two halves of the dipole act like the plates of a capacitor. Since like charges repel and unlike charges attract, the right half of the dipole has its maximum positive charge and the left half has its maximum negative charge. There is no current in the antenna at this instant since it now acts as a fully charged capacitor. Due to the difference in potential between the two halves of the antenna, an electric field is present around the antenna and the direction of the electric lines of force is from positive to negative, as indicated in the figure. There is no current at this instant and therefore there is no magnetic field around the antenna.

As the generator voltage decreases to zero, electrons flow from left to right in the wire to neutralize the charges on each half of the dipole. One-quarter of a cycle later this displacement current is at its maximum value and the generator voltage is zero. Figure 6B shows this phase of the cycle. Since the generator voltage is zero, there is no electric field around the antenna. However, since the current is maximum, the magnetic field around the wire is maximum and has the direction indicated in the figure. The arrowheads on the dipole of Figure 6B show the direction of the electron flow at this time.

During the remainder of the cycle, the generator voltage increases to a maximum of the opposite polarity and again decreases to zero. The electric field builds up to a maximum in the opposite direction, as shown in Figure 6C, and then decreases with the voltage. The current decreases to zero and

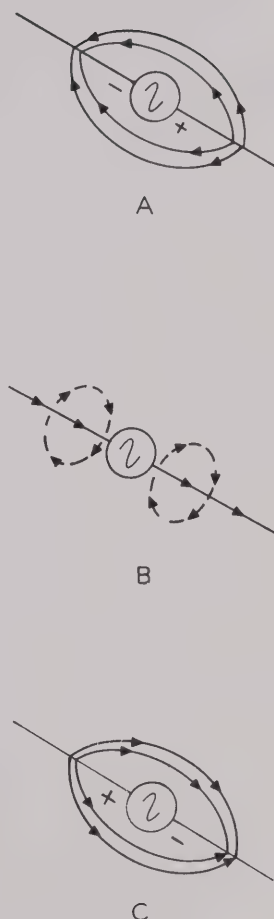


Figure 6

RADIO FREQUENCY EFFECTS

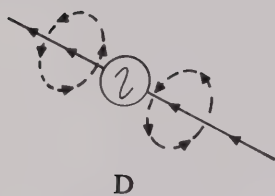


Figure
6

then builds up to a maximum in the opposite direction. There is no magnetic field when the current is zero, but as the current builds up in the opposite direction, the magnetic field also builds up to a maximum in the opposite direction, as shown in Figure 6D.

Figure 6 is only correct for static conditions, since it indicates that the electric and magnetic fields completely disappear during each alternation. Actually, the charges and currents are both changing at the frequency of the generator. If the generator had a very low frequency, Figure 6A through 6D would still apply fairly well. The electric lines of force would slowly build up while the ends of the antenna were being charged, would slowly collapse back into the antenna while the charges were being neutralized, and then would slowly build up again in the opposite direction while the antenna was being charged to the opposite polarity. Similarly, the magnetic flux lines would slowly build up while the current was increasing, would slowly collapse back into the antenna while the current was decreasing to zero, and then would slowly build up again in the opposite direction as the current increased in the opposite direction.

At radio frequencies the charges and currents change so rapidly that the electric and magnetic fields do not have time to completely collapse back into the antenna before new fields build up and push appreciable portions of the old fields away from the dipole as electromagnetic radiation.

The electromagnetic energy radiated into space from an antenna is known as the **RADIATION FIELD**. The electric and magnetic fields which collapse back into the antenna are known as the **INDUCTION FIELD**. The strength of the radiation field varies inversely with the distance from the antenna. The amplitude of the induction field, on the other hand, varies inversely as the square of the distance. Thus, the effect of the induction field is confined to distances a few wavelengths from the antenna.

As a radiated electromagnetic field passes through a conductor, some of the energy in the field produces an alternating current in the conductor having the same frequency as the electromagnetic radiation. Thus, an r-f current applied to a transmitting antenna can produce a similar r-f current (of much smaller amplitude) in a receiving antenna at a distant location. The characteristics of transmitting and receiving antennas are similar, so that a good transmitting antenna is usually a good receiving antenna.

Polarization

The term **POLARIZATION** is used to describe the direction of the electric and magnetic fields in an electromagnetic wave. The direction of polarization



The antenna system shown above is designed for tracking weather satellites. The antennas are circularly polarized since the signals transmitted by the satellites are circularly polarized as a result of their rotation.

of an electromagnetic wave is considered the same as the direction of the electric field of the wave. Thus, the electromagnetic energy of Figure 5 is vertically polarized because the electric lines of force are aligned in a vertical direction. If the fields of Figure 5 were rotated 90° so that the electric lines of force were aligned in a horizontal direction, the electromagnetic energy would be horizontally polarized. Under certain conditions, high-frequency radio waves can be circularly polarized. That is, the fields of the wave rotate—they are vertical at some instants and horizontal at others.

The term polarization is also used to describe antennas. Horizontally polarized antennas radiate horizontally polarized waves, and vertically polarized antennas radiate vertically polarized waves. The position of the antenna generally determines its polarization. An antenna that is mounted horizontally radiates horizontally polarized waves, and an antenna that is mounted vertically radiates vertically polarized waves.

Polarization is important because some r-f energy is lost when the polarization of the receiving antenna does not correspond to that of the electromagnetic

energy. Therefore, if the electromagnetic energy is horizontally polarized, the receiving antenna should also be horizontally polarized.

Reflection, Refraction and Diffraction

You are familiar with the **REFLECTION** of light by mirrors and other bright objects. The reflection of radio waves from a solid object is very similar to the reflection of light waves. This is to be expected because they are both electromagnetic radiations. This effect makes radar possible. In a radar set, the time required for a pulse of electromagnetic energy to reach an object and be reflected back to the radar set indicates the range or distance of the object from the antenna.

A radio wave produces currents in the object it strikes. These currents act like sources of electromagnetic energy and retransmit the original electromagnetic wave. Since the reflection of radio waves depends on this production of current in the reflecting object, good conductors make better reflectors than poor conductors.

You may have noticed that light waves bend as they pass from air to water or water to air. If you place a pencil in a glass of water, the pencil will appear to bend at the surface of the water. This is the reason it is necessary to aim below the target in spearing fish and in similar sports. This effect is called **REFRACTION**. It occurs whenever the velocity of an electromagnetic wave changes as it passes into a new medium. For example, radio waves are bent or refracted when they pass from air of one density to air of another density.

Charged layers of air in the upper atmosphere have different properties than the air at the earth's surface. These charged layers of air are called the **IONOSPHERE** and exist from about 70 miles to about 200 miles above the earth's surface. Radio waves passing into the ionosphere may be refracted and bent around enough to return to earth. Thus, radio waves can be reflected from the ionosphere in much the same way that they are reflected from solid objects. Radio waves reflected from the ionosphere reach the earth at long distances from the transmitter and make long-range, short-wave communication possible. The characteristics of the ionosphere vary with the time of day, the season of the year, and with the amount of sun spot activity, which in turn varies over a cycle of about 11 years.

Although mountains and other large barriers in the path of radio waves create radio "shadows", a small amount of the radio wave may be bent into the shadow zone by an effect called **DIFFRACTION**.

The diffraction of radio waves is less pronounced at high frequencies than at low frequencies. Therefore, radar uses radio waves of very high frequencies so that most of the waves travel to the target and are reflected from the target in straight lines. If the waves were diffracted around the target, they would also be reflected by objects in the shadow zone, and the reflected signal received at the radar set would give an inaccurate indication of the range.

Ground Waves, Sky Waves and Direct Waves

The portion of a radio wave that travels along the surface of the earth is called the GROUND WAVE. The portion of the wave that is radiated at any angle greater than the horizontal is called the SKY WAVE. Radio waves that travel between a transmitting antenna and a receiving antenna without being affected by either the ground or the upper atmosphere are called DIRECT WAVES.

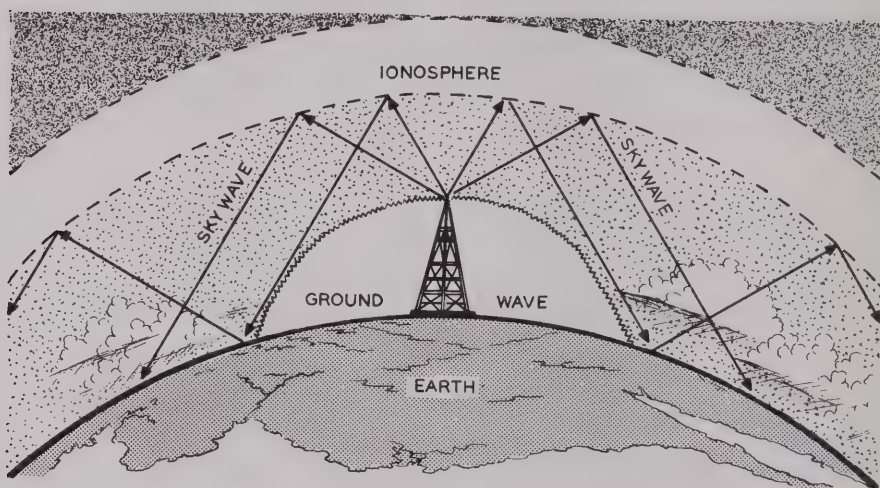


Figure 7

Figure 7 shows the ground waves and sky waves radiated by a transmitting antenna. The ground wave cannot travel far from the antenna before it is absorbed by the earth. Due to I^2R losses, low conductivity areas such as dry, rocky, and sandy earth absorb more energy than highly conductive areas such as wet earth and salt water. The earth also absorbs horizontally polarized ground waves much more quickly than vertically polarized waves. Thus, AM broadcast stations which depend on the ground wave for MOST of their coverage use vertical polarization. FM and TV stations, on the other hand, depend on direct waves and use horizontal polarization.

The sky wave travels upward through the atmosphere until it reaches the ionosphere. There, depending on the frequency of the wave, the characteristics of the ionosphere at the time, and the angle at which the wave strikes the ionosphere, the wave may pass into the upper atmosphere or be reflected back to earth. If the wave returns to the earth, it may be absorbed or reflected again by the earth's surface. The choice of the proper frequency for long-distance, sky-wave transmission is critical and must be carefully chosen.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

THE ELECTROMAGNETIC SPECTRUM

WAVELENGTH

PROPAGATION OF RADIO WAVES

THE DIPOLE ANTENNA

POLARIZATION

REFLECTION, REFRACTION AND DIFFRACTION

15. Radio frequency electrical energy and low frequency electrical energy can both be transmitted over wires. Which of these forms of energy can also be transmitted through space in the form of electromagnetic waves?
16. Which of the following is a form of electromagnetic wave? (a) light wave, (b) sound wave, (c) water wave.
17. Electromagnetic waves are classified according to what two characteristics?
18. The distance traveled by an electromagnetic wave during the time of one cycle is called a _____.
19. An antenna for an AM broadcast station is designed to be $\frac{1}{2}$ wavelength long. If the station frequency is 1.5 megahertz, the length of the antenna is (a) 112 meters, (b) 100 meters, (c) 1.5 meters, (d) 300 meters.
20. If the frequency of an electromagnetic wave increases, its wavelength (a) increases, (b) decreases, (c) remains the same.
21. In which type of radio receiver is the wiring and component layout more critical—AM or FM? Why?
22. In an electromagnetic wave, what is the relationship between the directions of the electric and magnetic fields and the direction of motion?
23. In a radar set, a pulse of electromagnetic energy requires 1 millisecond (.001 second) to travel from the radar set to a target and back to the radar set. How far has the energy traveled and how far is it from the radar set to the target? Give both distances in miles.
24. What fundamental law of electricity causes electrons to flow in a dipole antenna when a source voltage is applied to it?

25. The electron flow in an antenna produces a magnetic field. True or False?
26. Why is Figure 6 incorrect for radio frequencies?
27. What factor must be taken into consideration in making field strength measurements of the radiation field within a few wavelengths of the antenna?
28. The polarization of an electromagnetic wave is the same as the direction of the (a) electric field, (b) magnetic field of the wave.
29. For best reception, if a transmitting antenna is horizontally polarized, the receiving antenna should be (a) vertically polarized, (b) horizontally polarized.
30. Steel rods in a concrete wall reflect radio waves better than concrete. True or False?
31. How does the ionosphere affect radio waves?
32. Is diffraction more pronounced at high frequencies or at low frequencies?

Various organizations publish charts, based on the predicted characteristics of the ionosphere, which indicate the proper frequencies to use according to the time of day, year, and sun spot cycle.

Frequency and Propagation

The effects of reflection, refraction and diffraction depend to a large extent on the frequency of a radio wave. For example, reflection from solid objects is more pronounced at higher frequencies whereas diffraction is more pronounced at lower frequencies.

Figure 8 shows a table of a common classification of radio waves. Notice that the upper limit of each band after the first is 10 times its lower limit. Each band has slightly different propagation characteristics although there is no sharp distinction between any adjacent band.

FREQUENCY IN KILOHERTZ	DESIGNATION	ABBREVIATION
10-3X10	VERY-LOW FREQUENCY	VLF
3X10-3X10 ²	LOW FREQUENCY	LF
3X10 ² -3X10 ³	MEDIUM FREQUENCY	MF
3X10 ³ -3X10 ⁴	HIGH FREQUENCY	HF
3X10 ⁴ -3X10 ⁵	VERY-HIGH FREQUENCY	VHF
3X10 ⁵ -3X10 ⁶	ULTRA-HIGH FREQUENCY	UHF
3X10 ⁶ -3X10 ⁷	SUPER-HIGH FREQUENCY	SHF
3X10 ⁷ -3X10 ⁸	EXTREMELY-HIGH FREQUENCY	EHF

Figure 8

The Very-Low Frequency (VLF) band extends from 10 to 30 kilohertz. Because of the extremely long wavelengths of these frequencies, from 6 to 18 miles, the diffraction effect is very pronounced. Theoretically, even a low power VLF wave could be transmitted around the world by diffraction. In practice this is not possible with low power, however, because the earth absorbs so much power from the waves. Furthermore, since the length of

the antenna for such a low frequency signal is usually a small fraction of a wavelength, it is a poor radiator. Despite these power losses, however, VLF stations can still broadcast over a very great range. Some high power VLF stations are designed for transmitting around the world.

The Low Frequency (LF) band extends from 30 to 300 kilohertz. In this band, diffraction of the ground wave around the earth decreases and ground absorption losses increase. However, the shorter wavelengths in the LF band, as compared with those in the VLF band, make it possible to use much more efficient antennas. The VLF and LF bands are used where very reliable communications are necessary.

The Medium Frequency (MF) band extends from 300 kilohertz to 3 megahertz. The commercial AM broadcast band (535 kHz to 1605 kHz) lies within the MF band. Most MF transmission is by ground waves, although sky waves can be used at the higher end of the band during the daytime and over most of the band at night.

The High Frequency (HF) band extends from 3 to 30 megahertz. Most foreign broadcast stations and amateur radio stations operate in this band. The range for ground wave transmission of HF waves is only about 10 to 20 miles. During the day, however, various frequencies up to between 30 and 60 megahertz propagate for long distances by means of sky waves. At night, on the other hand, frequencies above 15 megahertz usually pass through the ionosphere and are lost.

The Very-High Frequency (VHF) band extends from 30 to 300 megahertz. The VHF television bands (54 MHz to 72 MHz, 76 MHz to 88 MHz, and 174 MHz to 216 MHz) and the commercial FM broadcast band (88 MHz to 108 MHz) lie within the VHF band. Since wavelengths at these frequencies are very short, little diffraction occurs. Therefore, the direct wave is used for most VHF transmission and the normal range of VHF waves is only slightly beyond the horizon. This direct-wave transmission is called line-of-sight transmission. Although sky-wave transmission is possible in the VHF band, it is usually limited to the lower frequencies. Ionospheric conditions are often such that the sky wave passes directly through the ionosphere with little refraction.

The Ultra-High Frequency (UHF) band extends from 300 megahertz to 3 gigahertz (3000 megahertz). The UHF television band (470 MHz to 890 MHz) lies within the UHF band, and some radar sets operate within this band. All communication in the UHF band is by direct waves.

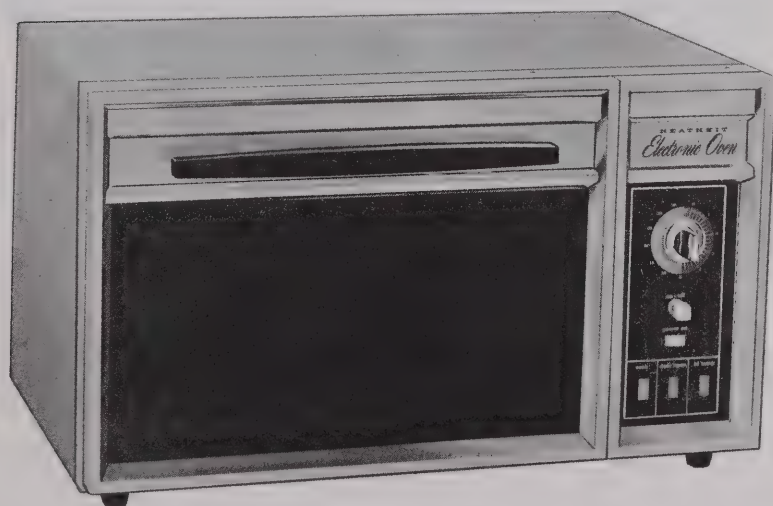
UHF antennas can be made highly directional. A highly directional transmitting antenna is one that concentrates the radiated energy into a narrow beam like the beam of light from a searchlight reflector. A highly directional receiving antenna is extremely sensitive in some directions and can detect very weak signals.

The Super-High Frequency (SHF) band extends from 3 gigahertz to 30 gigahertz. Most radar sets operate within this band. The wavelengths of radio waves within the upper portion of the UHF band and all of the SHF band are so short that they are called **MICROWAVES**. Lower frequency radio waves in the SHF band are highly directive and are free from most types of interference. However, higher frequency waves in the SHF band are absorbed by water vapor, by air, and by clouds.

The Extremely-High Frequency band extends from 30 gigahertz to 300 gigahertz. At the present time, this band is used primarily for experimental purposes.

RADIO FREQUENCY HEATING

Radio frequency currents and voltages can be used to heat various materials. There are two basic methods of r-f heating, called **INDUCTION HEATING** and **DIELECTRIC HEATING**. Induction heating is used to heat conduc-



Microwaves are useful for many purposes other than radio communications. For example, in the electronic oven shown above they are used to cook foods. The microwave energy evenly heats the food and cooks it in a much shorter time than is possible in a conventional oven.

Courtesy Heath Company

tors, and dielectric heating is used to heat nonconductors called dielectrics. Induction heating is used in the metal industry to heat-treat metals, and dielectric heating is used in the plastic, wood and food industries for curing, bonding, drying, dehydrating and similar processes. These are but a few of the many applications of r-f heating. Another form of dielectric heating, called **DIATHERMY**, is used to heat body tissue in the treatment of certain ailments and for the relief of pain.

Induction Heating

Figure 9 shows the principles involved in induction heating. The output of an alternating current source is applied to an induction heating coil. The work piece to be heated is placed in the magnetic field of the coil. This varying magnetic field produces eddy currents in the work piece, and the I^2R losses associated with the eddy currents heat the work piece.

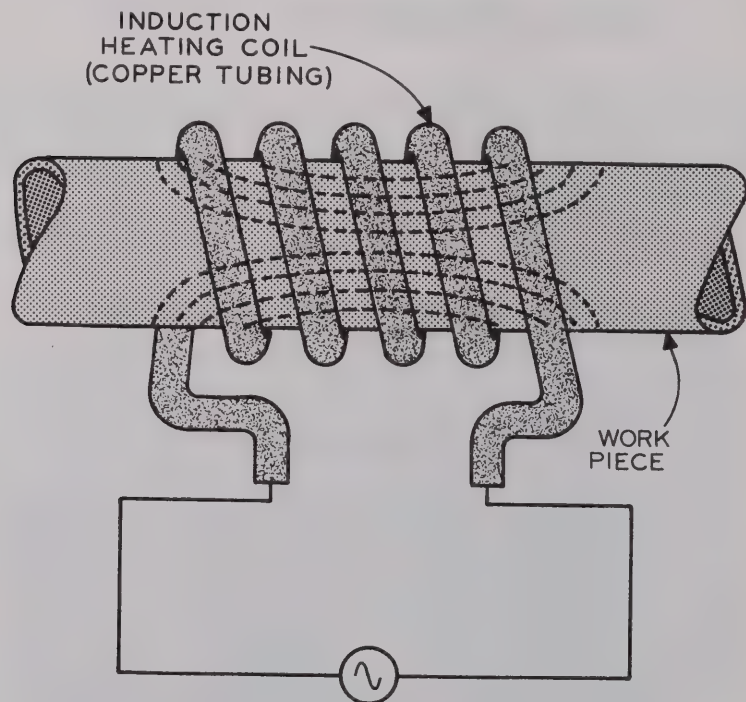


Figure 9

Induction heating is extremely flexible, since the material in the magnetic field can be heated either to a mild degree or to the melting point. In addition, the heat can be made to penetrate either completely through the material

or only a very slight distance from the surface. The penetration and temperature are determined by the strength and frequency of the magnetic field and the length of time the metal part is heated. Depending on the desired result, frequencies of from 60 hertz to many thousands of hertz are used in induction heating.

Dielectric Heating

Figure 10 shows the principles involved in dielectric heating. The output of a high frequency generator is applied to two electrode plates. The work piece (dielectric material to be heated) is placed between the two plates. The plates and dielectric act like a capacitor, and an electric field is produced between the two plates. Variations in the electric field cause the molecules of the dielectric to vibrate. This vibration of the dielectric molecules raises the temperature of the dielectric. The rise in temperature is uniform throughout the dielectric. This is an advantage over other forms of heating, which produce a more rapid increase of temperature near the surface of the material being heated.

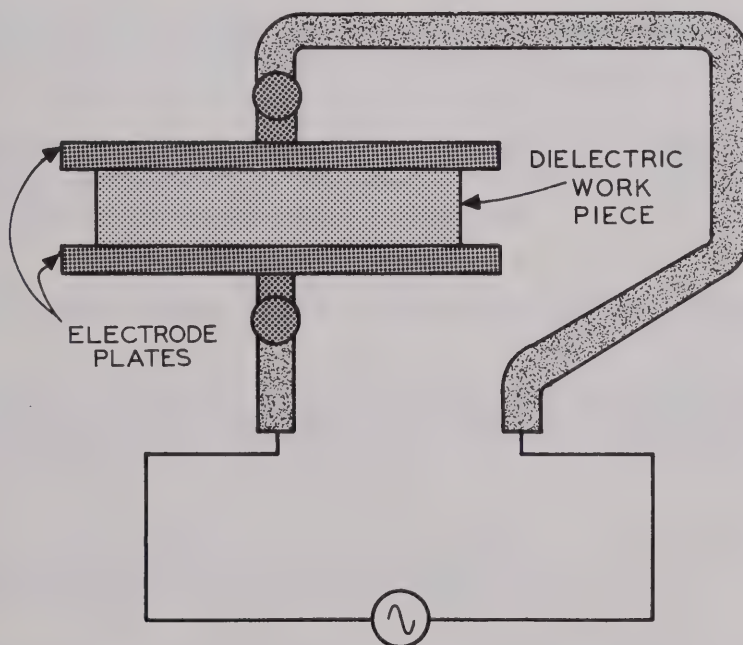


Figure 10

The temperature of the dielectric in Figure 10 is determined by the strength and frequency of the electric field. Depending on the desired result, frequencies from 1 to 50 megahertz and higher are used in dielectric heating.

Diathermy

In diathermy, two electrode plates, called space plates, are placed on either side of the portion of the body to be treated. An r-f voltage is applied across the plates, and the desired portion of the body is heated in the same manner as the dielectric material described previously.

There is considerable difference in the dielectric properties of different tissues. At lower r-f frequencies, heat is produced in fat tissues much more rapidly than in muscle tissue. At higher frequencies, however, this difference is much less pronounced. In the United States, the Federal Communications Commission (FCC) has set aside the frequencies of 13.56, 27.12 and 40.98 megahertz for short wave diathermy, and the band of frequencies between 2400 and 2500 megahertz for a newer form of diathermy called microwave diathermy.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

THE ELECTROMAGNETIC SPECTRUM

GROUND WAVES, SKY WAVES AND DIRECT WAVES

FREQUENCY AND PROPAGATION

RADIO FREQUENCY HEATING

INDUCTION HEATING

DIELECTRIC HEATING

DIATHERMY

33. Highly conductive areas of the earth absorb less energy from the ground wave than low conductivity areas. True or False?
34. Which of the following portions of the radio wave radiated by an antenna makes use of the ionosphere for long-distance transmission?
(a) ground wave, (b) sky wave, (c) direct wave.
35. Why are the antennas used in the VLF band usually poor radiators?
36. During the day, most commercial AM transmission is by ground waves alone, but at night both ground waves and sky waves are effective. True or False?
37. Long-distance transmission, farther than about 20 miles, in the HF band makes use of (a) sky waves, (b) ground waves.
38. Most transmission in the VHF band and all transmission in the UHF band is by (a) ground waves, (b) sky waves, (c) direct waves.
39. Most radar sets operate in the (a) HF band, (b) VHF band, (c) SHF band.

- 40. The term microwaves refers to what frequencies?**
- 41. Of the two basic methods of radio frequency heating, which is used to heat conductors and which is used to heat nonconductors?**
- 42. How is heat produced in the work in the induction heating process?**
- 43. In dielectric heating, heat is produced in the work piece by (a) eddy currents, (b) passing a dc current through the work, (c) the vibration of the molecules of the work piece.**

SUMMARY

At radio frequencies, effects which are not present in dc circuits and go unnoticed in low frequency circuits become very pronounced. All components have some resistive, inductive and capacitive properties. The leads of a resistor and the resistance element itself have inductance, and there is capacitance between the two terminals. The leads and plates of a capacitor have inductance, and the lead and dielectric losses make up a resistance. The conductor used to wind an inductor has resistance, and the many small capacitances between the windings of an inductor make up a distributed capacitance. Even the connecting wires in a piece of equipment may have considerable inductance. Although most of these properties are unimportant in low frequency circuits, they have considerable effect on radio frequency circuits.

Another important characteristic of radio frequency circuits is the difference between the dc and ac resistance of a conductor. Due to the skin effect, the ac resistance of a conductor may be many times the dc resistance.

Unlike low frequency energy, it is practical to transmit radio frequency energy through space, without the use of wires, as electromagnetic waves. The radio frequency band is only a small portion of the entire known electromagnetic spectrum. We generally think of radio frequencies as those frequencies between 10^4 hertz and 10^{11} hertz. In order of increasing frequency, other forms of electromagnetic energy are: infrared radiation, visible light, ultra-violet radiation, x-rays, gamma rays and cosmic rays.

An electromagnetic wave is made up of electric and magnetic fields at right angles to each other and to the direction of propagation. A radio wave is polarized in the direction of the electric field. A radio wave can be reflected, refracted, and diffracted in much the same way as light waves. Diffractive is more pronounced at low frequencies, and reflection is more pronounced at high frequencies. Refraction occurs whenever the velocity of an electromagnetic wave changes as it passes into a new medium.

The portion of a radio wave that travels along the surface of the earth is called the ground wave. The portion of the wave that is radiated at any angle greater than the horizontal is called the sky wave. Radio waves that travel directly from the transmitting antenna to a receiving antenna are called direct waves. Sky waves may be reflected back to earth by the ionosphere. This action makes possible long-distance, short-wave communications. A horizontally polarized ground wave is absorbed more rapidly by the earth than a vertically polarized ground wave.

Radio frequency heating is another important application of radio frequencies. Induction heating is used to heat conductors and dielectric heating is used to heat nonconductors, or dielectrics. A special form of dielectric heating, called diathermy, is used to heat body tissue in the treatment of certain ailments and for the relief of pain.

Induction heating operates on the principle that a varying magnetic field produces eddy currents in a conductor which, in turn, produce heat through I^2R losses. Dielectric heating operates on the principle that the molecules of a nonconductor vibrate in accordance with a varying electric field, thereby producing a change in the temperature of the material.

IMPORTANT DEFINITIONS

DIATHERMY — A form of dielectric heating used to heat body tissue in the treatment of certain ailments and for the relief of pain.

DIELECTRIC HEATING — A method of heating nonconductors, or dielectrics, by causing their molecules to vibrate under the influence of an electric field.

DIFFRACTION — The bending of electromagnetic waves around objects in their path.

DIPOLE — A type of antenna one-half wavelength long made up of two equal lengths of wire.

DIRECT WAVE — A radio wave that travels between a transmitting antenna and a receiving antenna without being affected by either the ground or the upper atmosphere.

DISTRIBUTED CAPACITANCE — A capacitance that is distributed over a large area as in a coil instead of being lumped into an individual component as in a capacitor.

DISTRIBUTED CONSTANTS — The properties of resistance, capacitance and inductance distributed over a large area as in a transmission line instead of being lumped into individual components.

ELECTROMAGNETIC WAVE — A form of wave made up of electromagnetic fields at right angles to each other and at right angles to the direction of propagation.

GROUND WAVE — The portion of a radio wave that travels along the surface of the earth.

INDUCTION FIELD — The portion of the field around an antenna that expands and collapses back into the antenna during each alternation.

INDUCTION HEATING — A method of heating conductors by means of eddy currents produced by a changing magnetic field.

IONOSPHERE — Charged layers of air in the upper atmosphere.

LUMPED CONSTANTS — The properties of resistance, capacitance and inductance lumped into individual components such as resistors, capacitors and inductors.

MICROWAVES — Radio waves near the high frequency end of the radio frequency spectrum having extremely short wavelengths.

IMPORTANT DEFINITIONS (Continued)

POLARIZATION — In reference to radio waves, the direction of the electric field—either vertical or horizontal.

QUALITY (Q) — A measure of the efficiency of a component or circuit. In reference to an inductor, Q is the ratio of its inductive reactance to its effective resistance.

RADIATION FIELD — The portion of the field around an antenna that is disengaged from the antenna and propagates itself through space in the form of electromagnetic waves.

RADIO FREQUENCIES — The band of frequencies at the low frequency end of the known electromagnetic spectrum ranging from about 10^4 hertz to about 10^{11} hertz.

REFLECTION — The turning back of an electromagnetic wave.

REFRACTION — The bending of an electromagnetic wave as it changes velocity passing into a new medium.

SKIN EFFECT — The tendency of an alternating current to concentrate along the surface of a conductor as the frequency is increased.

SKY WAVE — The portion of a radio wave radiated from an antenna at any angle greater than the horizontal. Some of the sky wave may be reflected back to earth by the ionosphere.

WAVELENGTH — The distance an electromagnetic wave travels during the time of one cycle.

ESSENTIAL SYMBOLS AND EQUATIONS

f — frequency (hertz)

Q — quality of a coil

R — dc resistance of an inductor (ohms)

X_L — inductive reactance of an inductor (ohms)

$\lambda(\text{ft})$ — the Greek letter lambda, representing wavelength in feet.

$\lambda(\text{m})$ — the Greek letter lambda, representing wavelength in meters.

$$Q = \frac{X_L}{R} \quad (1)$$

$$\lambda(\text{m}) = \frac{300,000,000}{f} \quad (2)$$

$$\lambda(\text{ft}) = \frac{984,000,000}{f} \quad (2a)$$

PRACTICE EXERCISE SOLUTIONS

1. True — Even a short piece of wire may have considerable inductive reactance at radio frequencies.
2. (b) along the surface of a conductor. — Since the magnetic flux lines associated with an r-f current are more concentrated in the center of a conductor, there is more opposition to the current at the center of the conductor.
3. The ac resistance — Because of the skin effect, the ac resistance of a conductor may be many times greater than the dc resistance.
4. litz conductors and large diameter tubing — Litz conductors are made up of a number of small diameter, interwoven, separately insulated strands of wire. Both litz conductors and large diameter tubing provide a large effective surface area to carry current.
5. False — Wirewound resistors have much greater inductances than composition types.
6. At the resonant frequency of its reactive components, the impedance of a resistor is greater than its resistance.
7. At frequencies above resonance. — Since a capacitor has resistance and inductance as well as capacitance, it acts like an inductance in series with a resistance at frequencies above the series resonant frequency.
8. The inductance of tubular capacitors has a pronounced effect at radio frequencies.
9. The many small capacitances between the turns of the inductor.
10. The natural resonant frequency should be higher than the applied signal frequency.
11. The distributed capacitance of the inductor is used as the capacitive portion of a parallel tuned circuit.
12. 30 — Using Equation 1:

$$\begin{aligned}
 Q &= \frac{X_L}{R} \\
 &= \frac{3000}{100} \\
 &= 30.
 \end{aligned}$$

PRACTICE EXERCISE SOLUTIONS (Continued)

13. It increases the Q because it increases the inductance without changing the effective resistance.
14. (1) It is much easier to obtain the required small values of inductance and capacitance in a transmission line. (2) Resonant transmission lines have much higher values of Q than can be obtained with lumped constants.
15. Radio frequency electrical energy is commonly transmitted through space in the form of electromagnetic radiation.
16. (a) light wave.
17. frequency and wavelength.
18. wavelength.
19. (b) 100 meters — First using Equation 2:

$$\begin{aligned}\lambda(\text{m}) &= \frac{300,000,000}{f} \\ &= \frac{300 \times 10^6}{1.5 \times 10^6} \\ &= 200 \text{ meters}\end{aligned}$$

Now dividing by 2 to obtain $\frac{1}{2}$ wavelength gives 100 meters.

20. (b) decreases — frequency and wavelength are inversely proportional.
21. FM — Because FM radio uses a much higher frequency than AM radio, effects such as skin effect, distributed capacitance and lead inductance are much more pronounced.
22. The electric and magnetic fields are at right angles to each other and at right angles to the direction of wave motion.
23. Since electromagnetic energy travels at a speed of 186,000 miles per second, it will travel 186 miles ($186,000 \times .001$) in 1 millisecond. This is the distance traveled by the electromagnetic energy from the radar set to the target and back again. The distance from the radar set to the target is one-half of 186 miles, or 93 miles.
24. The fact that like charges repel and unlike charges attract. Thus, electrons are attracted to the positive terminal of the source, and are repelled by the negative terminal.

PRACTICE EXERCISE SOLUTIONS (Continued)

- 25. True.
- 26. It indicates that the electric and magnetic fields completely disappear during each alternation.
- 27. At distances less than a few wavelengths from an antenna, the induction field still has appreciable amplitude and must be taken into consideration in making field strength measurements of the radiation field. For this reason, field strength measurements of the radiation field are usually taken at distances equal to many wavelengths from the antenna.
- 28. (a) electric field.
- 29. (b) horizontally polarized.
- 30. True — Steel rods are a better conductor than concrete.
- 31. Radio waves may be refracted and even reflected by the ionosphere.
- 32. At low frequencies.
- 33. True.
- 34. (b) sky wave.
- 35. The antennas used at these frequencies (VLF) are usually a small fraction of a wavelength. Since a wavelength at these frequencies extends from 6 to 18 miles, it is usually impractical to construct antennas which are appreciable portions of a wavelength.
- 36. True.
- 37. (a) sky waves. — The range for ground wave transmission of HF waves is only about 10 to 20 miles.
- 38. (c) direct waves.
- 39. (c) SHF band.
- 40. Those in the upper portion of the UHF band and all of the SHF band.
- 41. Induction heating is used to heat conductors, and dielectric heating is used to heat nonconductors.
- 42. An alternating current is applied to a coil which sets up a varying magnetic field. The varying magnetic field produces eddy currents in the work, and these currents produce heat in the form of I^2R losses.
- 43. (c) the vibration of the molecules of the work piece.

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1073A

EXAMINATION

CHECK SHEET

1. B - AT HIGH FREQUENCIES -- CURRENT TENDS TO CONCENTRATE AT THE SURFACE OF A CONDUCTOR.

With an alternating current in a conductor the magnetic lines are more concentrated at the center than near the surface.

2. A - SUPPOSE AN INDUCTOR HAS A VALUE OF 10 mH AND A DC RESISTANCE OF 100 OHMS. WHAT IS ITS Q AT AN OPERATING FREQUENCY OF 10 kHz? -- 6.28.
The inductive reactance at 10 kHz is:

$$X_L = 2\pi fL = 6.28 \times 10 \times 10^3 \times 10 \times 10^{-3} = 6.28 \times 10^2 = 628 \text{ ohms}$$

The Q is then equal to

$$Q = \frac{X_L}{R} = \frac{628}{100} = 6.28$$

3. B - THE WAVELENGTH OF AN ELECTROMAGNETIC WAVE IS -- THE DISTANCE IT TRAVELS DURING THE TIME OF ONE CYCLE.

The distance traveled during one cycle is equivalent to the distance between two corresponding points on neighboring cycles.

4. A - WHAT IS THE WAVELENGTH IN FEET OF A 4.5 MHz WAVE? -- 219 FEET.
Wavelength in feet is equal to:

$$\lambda \text{ (feet)} = \frac{984,000,000}{f} = \frac{984}{4.5} = 219 \text{ feet (approximately)}$$

5. A - AN ELECTROMAGNETIC WAVE IS MADE UP OF -- BOTH ELECTRIC AND MAGNETIC FIELDS.
The electric and magnetic fields are at right angles to each other and at right angles to the direction of propagation.

6. B - A DIPOLE ANTENNA IS -- 1/2 WAVELENGTH LONG.
The total length of a dipole antenna is 1/2 wavelength, and the antenna is often called a half-wave dipole.

7. C - THE POLARIZATION OF AN ANTENNA IS THE SAME AS -- THE DIRECTION OF THE ELECTRIC FIELD.
Transmitting and receiving antennas should have the same polarization to obtain maximum efficiency.

8. B - THE FREQUENCY RANGE OF THE HF BAND IS -- 3 TO 30 MHz.
Most foreign broadcast stations operate in the 3 to 30 MHz (HF) band. Propagation over long distances is carried out by sky waves in this band.

9. B - MOST RADAR SETS OPERATE IN THE -- SHF BAND.
The SHF band (3 gigahertz to 30 gigahertz) is often referred to as the microwave band of frequencies.

10. B - INDUCTION HEATING CAN BE USED TO HEAT -- STEEL.
Induction heating is used to heat conducting materials like steel. Nonconductors are heated by using dielectric heating techniques.

1073A



EXPERIMENT 5

HIGH PASS AND LOW PASS FILTERS

PARTS NEEDED

- | | |
|--|-------------------------------|
| 1 - Complete Design Console | 1 - .1 μ F Disk Capacitor |
| 1 - Multimeter with Test Leads and Spring Adapters | 1 - 400 Ω Relay |
| 1 - 1 k Ω , 1/2 W, 20% Resistor | 3 - Modular Connectors |
| 1 - 4.7 k Ω , 1/2 W, 20% Resistor | - No. 22 Solid Hookup Wire |

OBJECTIVE

In this experiment you will investigate the action of RL and RC high pass and low pass filter circuits.

PART 1

PROCEDURE

RL FILTERS

1. Set up the low pass RL filter circuit of Figure 5-1 on the design console. The relay coil is used as the circuit inductance. Be sure to use the sinewave output of the audio generator. The low voltage dc power supply is not used, so set the ADJUST VOLTAGE control fully counterclockwise.
2. Use the output function of your multimeter to measure the ac output from the circuit developed across R_1 . Set the audio generator ADJUST FREQ. control to each of the frequencies listed in the chart of Figure 5-2, and record the output voltages (E_O) in the chart.
3. Using the data from the chart of Figure 5-2, plot the curve of the output voltage versus frequency on the graph of Figure 5-3.

Your curve should have the general appearance of that shown on Figure 5-4. Note from your data that as the frequency is increased from the 0 on the dial, the filter output remains relatively constant until the "roll off" (or "corner") frequency is reached, then the output voltage of a low pass filter circuit decreases. This frequency is determined by the values of L_1 and R_1 (where $X_{L_1} = R_1$) and is the frequency where the output of a low pass filter starts to fall as the frequency steadily increases.

4. Set up the high pass RL filter circuit of Figure 5-5 on your design console. (This is the same circuit as that of Figure 5-1 except that the output is now taken across the inductor.) Again, be sure to use the sinewave output of the audio generator. The ADJUST VOLTAGE control should be set fully counterclockwise

9506

since the low voltage power supply is not used.

5. Measure the filter ac output voltage at each of the frequency settings listed in the chart of Figure 5-6, and record your results. Use the output function of your multimeter to measure the output voltage.

6. Plot a curve of output voltage (E_O) versus frequency for the circuit on the graph of Figure 5-7, using the data in the chart of Figure 5-6.

Your curve should have the general appearance of the one shown in Figure 5-8. In a high pass filter circuit, the output increases as frequency increases until the "roll-off" frequency is reached, after which the output is constant. This is opposite to the action in a low pass filter circuit.

PART 2

PROCEDURE

RC FILTERS

1. Set up the low pass RC filter circuit of Figure 5-9 on your design console. The ADJUST VOLTAGE control should be fully counterclockwise since the low voltage power supply is not used.

2. Using the output function of your multimeter, measure the filter's output voltage at each of the frequencies listed in the chart of Figure 5-10. Record the voltages in the chart of Figure 5-10.

3. Using the data in the chart of Figure 5-10, plot a curve of the output voltage versus frequency on the graph of Figure 5-11. Your curve should have the same general appearance as the RL low pass filter curve in Figure 5-4. The "roll off" frequency will probably be different due to different component values, but it is the frequency where $X_{C_1} = R_1$.

4. Now set up the high pass RC filter circuit of Figure 5-12 on your design console. (This is the same circuit as that of Figure 5-9, except that the output is now the voltage across the resistor.)

5. Record the filter's output voltage for each frequency listed in the chart of Figure 5-13.

6. Plot a curve of output voltage versus frequency on the graph of Figure 5-14, using the data in the chart of Figure 5-13. The characteristics of the high pass RC filter should be similar to those shown for the high pass RL filter in Figure 5-8.

High Pass and Low Pass Filters

CONCLUSION

The circuit action in RL and RC high pass and low pass filter circuits is the same. In a low pass filter circuit, the output voltage remains constant as the signal frequency increases; then, when the roll-off frequency is reached, the output decreases with increasing frequency. On the other hand, in a high pass filter circuit, the output voltage increases as the signal frequency increases until the roll-off frequency is reached, above which an increase in frequency causes no increase in output.

NOTES

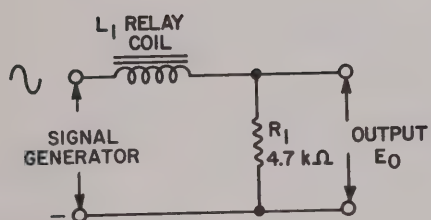


FIGURE 5-1

FREQ	E ₀
0	
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

FIGURE 5-2

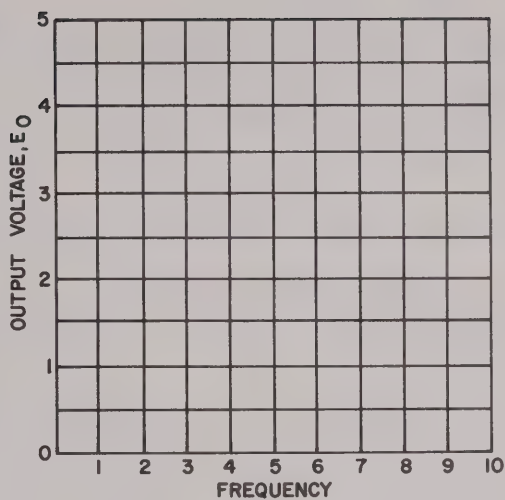


FIGURE 5-3

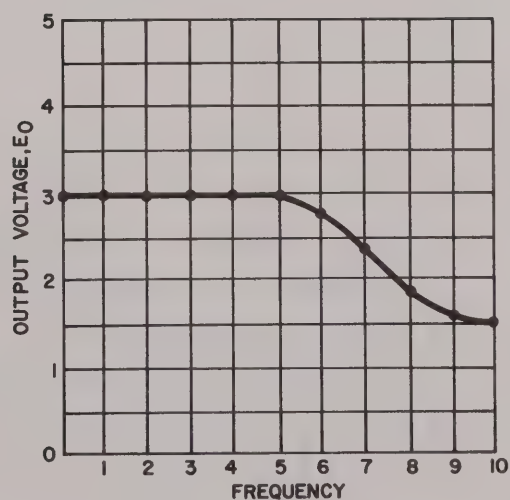


FIGURE 5-4

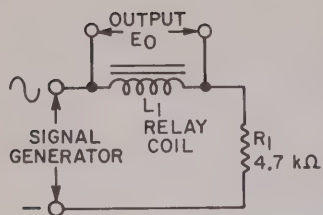


FIGURE 5-5

FREQ.	E ₀
0	
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

FIGURE 5-6

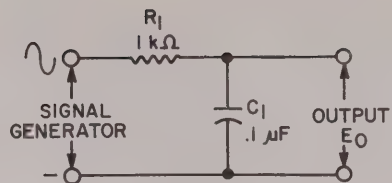


FIGURE 5-9

FREQ.	E ₀
0	
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

FIGURE 5-10

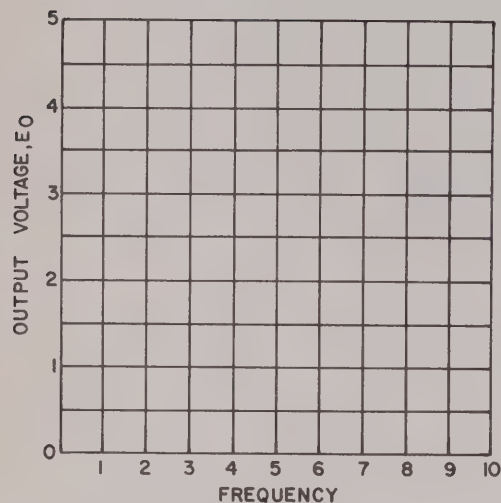


FIGURE 5-7

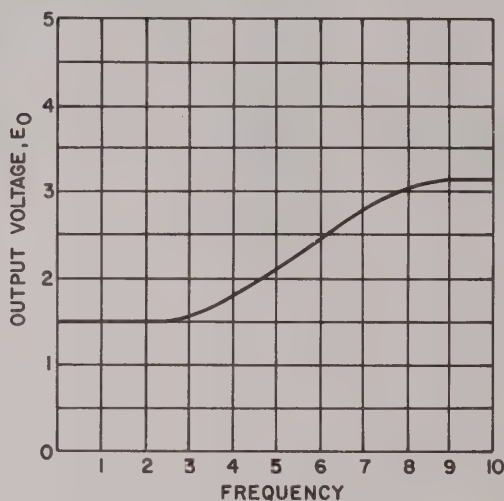


FIGURE 5-8

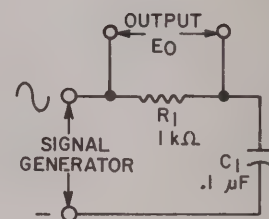


FIGURE 5-12

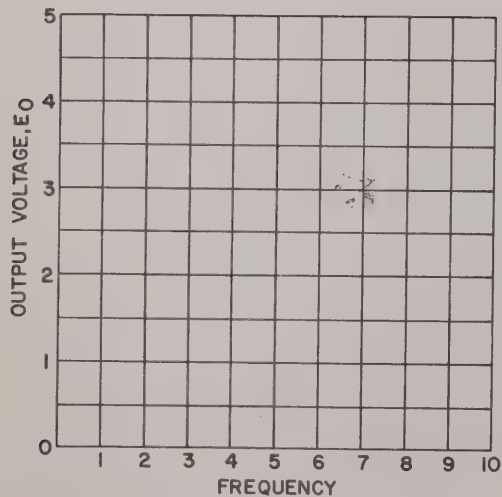


FIGURE 5-11

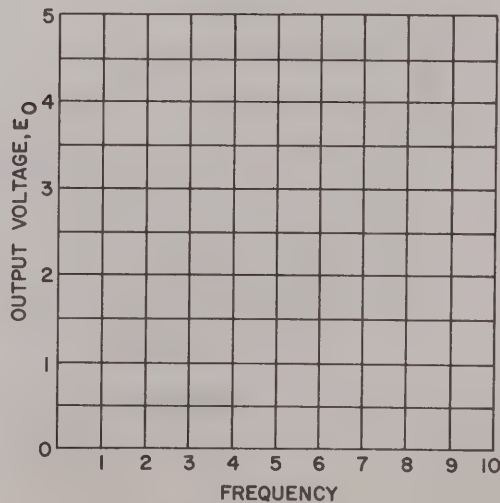


FIGURE 5-14

FREQ.	E ₀
0	
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

FIGURE 5-13



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EXAMINATION
CHECK SHEET

1. C - IN A LOW PASS FILTER CIRCUIT, -- AS FREQUENCY DECREASES, THE OUTPUT INCREASES.
The output decreases as frequency increases in a low pass filter circuit.

2. C - REFERRING TO A SERIES RL FILTER CIRCUIT, -- THE OUTPUT IS TAKEN ACROSS L FOR A
HIGH PASS CIRCUIT.

In an RL filter circuit, the output is taken across R for a low pass circuit and across L for a high pass circuit.

3. A - IN A HIGH PASS FILTER CIRCUIT, THE OUTPUT -- DECREASES AS FREQUENCY DECREASES.
The output increases as frequency increases in a high pass filter circuit.

4. A - REFERRING TO A SERIES RC FILTER CIRCUIT, -- THE OUTPUT IS TAKEN ACROSS THE
RESISTOR FOR A HIGH PASS CIRCUIT.

In an RC filter circuit, the output is taken across R for a high pass circuit and across C for a low pass circuit.

5. C - SUPPOSE THAT IN THE CIRCUIT OF FIGURE 5-1 THE INDUCTANCE OF L_1 IS INCREASED.
THE RESULT WILL BE -- A DECREASE IN THE "ROLL-OFF" FREQUENCY.

If L is made larger, X_{L_1} becomes equal to R_1 at a lower frequency, thus reducing the "roll-off" frequency.

1.

2.

3.

4.

5.

6.

7.

8.

9.

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10

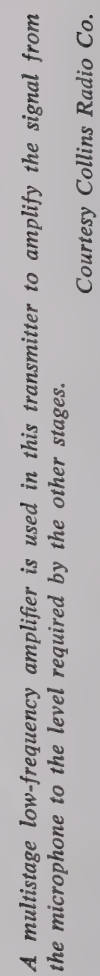


VACUUM TUBE LOW-FREQUENCY AMPLIFIERS

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A multistage low-frequency amplifier is used in this transmitter to amplify the signal from the microphone to the level required by the other stages.

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*A problem, all too often, is merely the absence of an idea.
—Good Impressions*

VACUUM TUBE LOW-FREQUENCY AMPLIFIERS

The term "low frequencies (l-f)" applies to frequencies between 0 Hz and 100,000 Hz. Some low-frequency amplifiers are designed to amplify signal frequencies between 20 Hz and 20,000 Hz. Since this is the approximate range of the audio frequencies, these low-frequency amplifiers are often called AUDIO-FREQUENCY AMPLIFIERS, or simply AUDIO AMPLIFIERS.

In this lesson we shall analyze vacuum tube low-frequency amplifiers. In addition to discussing their circuits, many of the problems involved in the construction and operation of low-frequency amplifiers will be considered.

VOLTAGE AMPLIFIERS

When an electron tube builds up a relatively weak input voltage to a higher value, it is called a **VOLTAGE AMPLIFIER**. The output voltage may be further amplified by applying it to the grid circuit of another tube. The tube and its associated circuits are known as a stage. When a signal passes through two or more stages in sequence, such circuits are called CASCADE STAGES.

Associated with each voltage amplifier stage is a factor known as **VOLTAGE GAIN (A_V)**. The voltage gain of an amplifier is the ratio of the output voltage to the input voltage. In the form of an equation:

$$A_V = \frac{E_O}{E_{IN}} \quad (1)$$

where: E_O is the output signal voltage across the load,

E_{IN} is the input signal voltage, and

A_V is the voltage gain.

The use of this equation may be illustrated by the following example. Suppose E_{IN} is 1 volt and E_O is 10 volts. The voltage gain may be found from Equation 1 as follows:

$$A_V = \frac{E_O}{E_{IN}} = \frac{10}{1} = 10.$$

The gain of a voltage amplifier stage may also be expressed in terms of the circuit components and tube factors:

$$A_v = \frac{\mu \times R_L}{R_L + r_p} \quad (2)$$

where: μ is the Greek letter mu representing the amplification factor of the tube,

R_L is the plate load resistance, and

r_p is the dynamic plate resistance of the tube.

Assume that a tube has an amplification factor (μ) of 20, a plate resistance (r_p) of 5000 ohms, and operates with a load resistance of 10,000 ohms. According to Equation 2, the voltage gain for the stage is:

$$\begin{aligned} A_v &= \frac{\mu \times R_L}{R_L + r_p} = \frac{20 \times 1 \times 10^4}{1 \times 10^4 + 5 \times 10^3} \\ &= \frac{2 \times 10^5}{1.5 \times 10^4} = 13.33 \end{aligned}$$

If a .1-volt signal (E_{IN}) is applied to the grid of a tube, the output voltage (E_o) may be found by rearranging Equation 1.

Multiply both sides by E_{IN} :

$$A_v E_{IN} = \frac{E_o E_{IN}}{E_{IN}}$$

or

$$E_o = E_{IN} A_v.$$

Substituting the values for E_{IN} and A_v , we get:

$$E_o = .1 \times 13.35 = 1.333 \text{ volts.}$$

When more than one stage is used, **THE TOTAL AMPLIFIER GAIN IS THE PRODUCT OF THE VOLTAGE GAINS OF THE INDIVIDUAL STAGES.** For instance, if an amplifier has three stages, each with a voltage gain of 10, the overall gain is:

$$10 \times 10 \times 10, \text{ or } 1000.$$

As another example, a two-stage amplifier with stage gains of 8 and 12 has a total gain of:

$$8 \times 12 = 96.$$

POWER AMPLIFIERS

Although the output voltage of a voltage amplifier is stepped up considerably, the actual power output may remain quite small. If the signal must operate a loudspeaker, a sound recording mechanism or a mechanical control, or "drive" a transmitter stage which requires appreciable power, a **POWER AMPLIFIER** must be added.

These situations require a **POWER TUBE** or a combination of tubes that provide the desired power output. The average power tube has a lower internal resistance than a voltage amplifier tube, and therefore, higher plate currents can be obtained. The maximum plate voltage that can be applied safely to a power tube is limited only by the current the tube can carry without overheating.

Even though the voltage increase or gain of a power tube is low, the power gain can be quite high. A grid input signal of a fraction of a watt results in an output of several watts.

AMPLIFIER CLASSIFICATION

Amplifiers are classified according to the length of time that plate current exists during each input signal cycle. Accordingly, there are three major classes: A, B and C.

In a **CLASS A AMPLIFIER**, plate current exists during the entire 360° of the input signal cycle. In a **CLASS B AMPLIFIER**, plate current exists during half, or 180° , of the cycle. In a **CLASS C AMPLIFIER**, plate current exists for less than half the cycle. These major amplifier classes also are found in a number of variations or combinations.

When an amplifier's output waveform is not exactly the same shape as the input signal, a condition known as **DISTORTION** exists. A Class A amplifier produces the least amount of distortion. In certain applications, circuits are purposely designed to produce distortion so that the desired output waveform can be obtained. However, for most low-frequency amplifiers the distortion is kept to a minimum. Because Class C amplifiers produce severe distortion, they are not generally used as low-frequency amplifiers, and will therefore not be discussed in this lesson.

Class A Amplifiers

The length of time that plate current exists during an input signal cycle is controlled by a tube's grid bias and the ac signal voltages used. In Figure 1,

the bias is provided by E_{cc} . The input signal is developed by the generator voltage, E_{IN} . Usually, in the Class A amplifier, the bias and signal voltages are chosen to confine tube operation to the straight portion of the grid voltage-plate current characteristic curve.

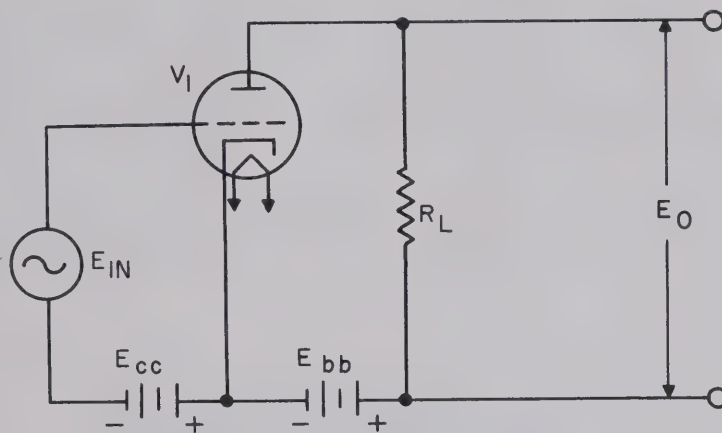


Figure 1

Using the characteristic curves of Figure 2, the grid bias, E_c (operating point of the tube), is -3 volts. This is shown by the dashed vertical line labeled E_c . The input signal, E_{IN} , has a peak value of 3 volts. During the positive alternation, the input signal voltage opposes the grid bias and reduces the grid voltage from -3 to 0 volts. During the negative alternation, the signal voltage aids the bias to increase the negative grid voltage from -3 to -6 volts.

The grid does not become positive at any time, nor does the voltage applied to it exceed -6 volts. Projecting the resultant grid voltages up to the characteristic curve (by means of the dashed lines) shows that the tube operates above the bend at the lower end of the curve and below the bend at the upper end. This confines the grid voltages to the straight, or LINEAR portion, of the curve.

The plate current varies in direct proportion to grid voltage changes, as long as the tube operation is linear. Very little distortion is produced by a tube operating on the linear portion of its characteristic curve. In Figure 2, for example, as the grid voltage increases from -3 to -6 (a change of 3 volts), the plate current decreases from 2.3 to $.5$ mA (a change of 1.8 mA). A grid voltage change from -3 to 0 volts (a change of 3 volts) produces

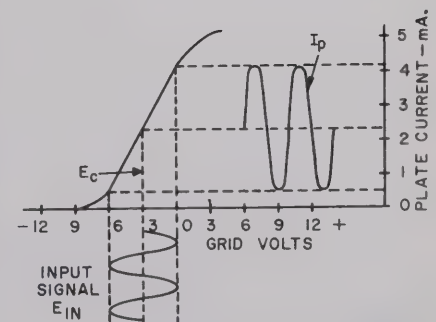


Figure 2

VACUUM TUBE LOW-FREQUENCY AMPLIFIERS

a plate current increase from 2.3 to 4.1 mA (a change of 1.8 mA). Thus, for equal changes of 3 volts on the grid, there are equal changes of 1.8 mA in plate current. Therefore, the ac component of the plate current is an amplified replica of the original signal applied to the grid.

If the magnitude of the input signal voltage is increased beyond 3 volts, the grid swings into the positive region, causing some of the emitted electrons to be attracted to it instead of the plate. This diversion of electrons reduces the magnitude of plate current. As a result, the waveform of the signal is not reproduced correctly in the plate circuit, and serious distortion results.

If an attempt is made to correct this condition by increasing the negative bias, the operating point shifts to the left, causing the tube to operate on the nonlinear, lower portion of the curve, as shown in Figure 3. Now, with the tube biased at -4 volts and the input signal increased to 4 volts peak, when the signal swings the grid voltage from -4 volts to 0 volts, the plate current increases from 1.8 to 4.1 mA for a change of 2.3 mA. When the grid voltage swings 4 volts from -4 to -8 volts, the plate current goes from 1.8 to .2 mA for a decrease of only 1.6 mA.

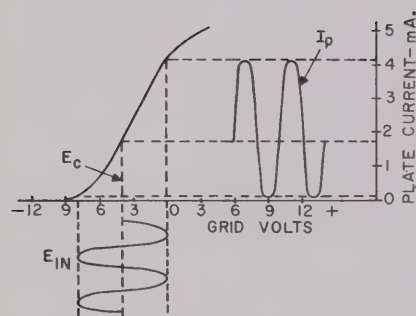


Figure
3

Therefore, equal changes in grid voltage no longer produce equal plate current changes. The ac component of the plate current has one alternation larger than the other. For this reason, the signal output of the Class A amplifier is limited by the magnitude of the input signal it can handle without excessive distortion. THIS POWER OUTPUT USUALLY IS ABOUT ONE-FOURTH, OR 25%, OF THE DC POWER SUPPLIED TO THE TUBE BY THE PLATE POWER SUPPLY.

The efficiency of an amplifier is the ratio of the power out to the power in. The efficiency of a Class A power amplifier is poor. A maximum efficiency of 25% is obtainable with triodes, and 30% with tetrodes and pentodes. Note: Efficiency concerns the dc power input to the stage from the power supply, not the signal input.

The numeral "1" sometimes is added as a subscript to the letter or letters of an amplifier classification to signify that no grid current exists during any part of the signal input cycle. Therefore, the operation of the circuits represented by Figures 2 and 3 may be designated as Class A₁.

When a numeral "2" is added as a subscript, it signifies that grid current does exist for some portion of the input signal cycle. As already explained, since electrons are diverted from the plate, this type of operation produces

distortion, and the output efficiency is even lower than for a Class A_1 amplifier. Therefore, A_2 operation seldom is used. The letter A without any subscript indicates Class A_1 operation.

Class B Amplifiers

To obtain greater efficiency, amplifier tubes may be operated Class B. For Class B operation, the grid bias is increased until it is approximately equal to the plate current cutoff voltage. This means that, with no input signal voltage, the plate current is practically zero. When the signal voltage is applied to the grid, current exists only for the positive alternation of the signal cycle.



The voltage amplifiers in an oscilloscope are operated Class A to obtain a minimum amount of distortion.

Courtesy Heath Co.

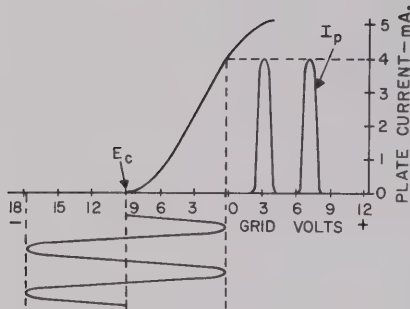


Figure 4

Class B operation is illustrated by Figure 4. The operating point, E_c , has been shifted to the bottom of the curve, the plate current cutoff point, by adjusting the grid bias to -9 volts. The signal E_{IN} now can be increased to a peak of 9 volts without causing the grid to go positive.

With no input signal, there is no plate current. However, during the positive signal alternations the negative grid bias is partially canceled to permit plate current. During the negative signal alternation, the negative bias is merely increased, and since the tube is already cut off, there is no plate current. With the current pulses occurring only during the positive alternations, the increase of plate current is determined by the magnitude of the signal voltage. Since power is supplied to the circuit only during the intervals of plate current, plate dissipation takes place about one-half of the total cycle. Therefore, the efficiency averages between 50 and 65 percent, much higher than is obtained in Class A operation.

Because the amplifier has higher efficiency, it is possible to apply more voltage to the plate without overheating the tube. Therefore, in Class B operation, much larger current pulses can be handled than may be used during the continuous Class A operation. This is because the Class B tube has an opportunity to cool between pulses.

Class B operation also allows use of a much larger input signal voltage without driving the grid positive. As an example in which the same tube is used, the Class A operation shown in Figure 2 limits the grid signal to a 3 -volt peak, while the Class B operation of Figure 4 permits a grid signal peak of almost 9 volts.

A tube Class B operated acts like a half-wave rectifier, and therefore, a single tube cannot be used to amplify low-frequency signals, because of the excessive distortion. However, it is possible to use two tubes in Class B operation to obtain an efficient audio amplification by using the push-pull circuit described later in this lesson.

Class AB Amplifiers

A CLASS AB AMPLIFIER is one in which the grid bias and ac signal voltages produce plate current for more than half but less than the entire signal voltage cycle. The grid bias voltage for this type of amplifier is in between the voltages used for Class A or Class B operation.

In Class AB operation, plate voltages can be made higher than for Class A because the increased negative bias limits the amount of conduction. Like Class B, the maximum plate dissipation rating is less likely to be exceeded. The higher plate voltages result in greater power output than is possible in Class A operation.

GRID BIAS METHODS

The class of an amplifier is determined by the length of time plate current exists during each input cycle. Therefore, the proper operation of electron tube circuits depends upon the grid bias.

Separate Supply

When a very stable grid voltage is needed, a separate grid supply voltage is employed, as shown in Figure 5. The negative bias voltage is applied through the grid load resistor (R_{IN}). In most cases, a separate power supply or voltage divider arrangement is used to provide the bias.

The separate grid supply voltage (E_{cc}), shown in Figure 5, provides what is called **FIXED BIAS**. This type of bias is very often employed in Class B or Class C amplifiers when the required operating point is at, near or beyond plate current cutoff.

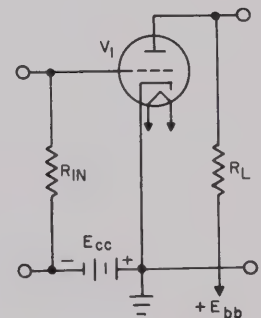


Figure 5

Cathode Bias

Many amplifiers employ **SELF-BIAS**, as shown in Figure 6. The necessary bias is developed as a result of the voltage drop across cathode resistor R_1 . For this reason, the arrangement is also referred to as **CATHODE BIAS**.

With no input signal, there is a steady plate current from ground up through R_1 , from the cathode to the plate, down through R_L to E_{bb} and back to ground. By Ohm's Law ($E_{R_1} = I_b R_1$), a steady voltage drop exists across R_1 , with the end that is connected to the cathode positive with respect to ground. Since the lower end of R_{IN} is connected to ground, or to a point that is negative with respect to the cathode, the control grid is also negative with respect to the cathode.

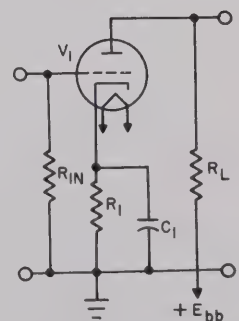


Figure 6

For example, if E_{R_1} is 3 volts, then the grid bias with no input signal is -3 volts. There is no current in R_{IN} ; it is used to apply the negative bias voltage to the control grid, and also to develop the input signal.

When a signal is applied to the control grid (across R_{IN}), the plate current varies. Therefore, the voltage drop across R_1 would change too, were it not for capacitor C_1 which acts as a voltage stabilizer to eliminate the undesired voltage variation.

An RC combination of this type with a long time constant prevents the voltage across R_1 from varying. With a steady current, the fixed voltage drop across R_1 charges C_1 until the voltage across the capacitor is equal to the drop across the resistor. Then, when the current decreases, C_1 has to discharge through R_1 before its voltage can decrease. If the R_1C_1 time constant is large, not enough electrons discharge through R_1 to permit an appreciable change in voltage before the input signal causes the current to increase again.

The charge and discharge of C_1 maintains a constant current through and a constant voltage across R_1 , in spite of plate current changes. Thus, C_1 has the effect of passing the alternating portion of the plate current around the resistor. For this reason, C_1 often is called a **CATHODE BYPASS CAPACITOR**.

To obtain the desired long time constant for the cathode bias network, a large value of capacitance is required. This large value is necessary because the resistance of R_1 is normally low. Since large value capacitors are expensive, the minimum value of capacitance which gives satisfactory results is usually selected.

It is sometimes convenient to think that the cathode bypass capacitor offers very low reactance to the ac component and very high resistance to the dc component, while the resistor offers equal resistance to both.

A good rule of thumb is to select C_1 so that its reactance at the lowest frequency to be amplified is 1/10 the resistance of R_1 . For example, assume that R_1 of Figure 6 is a 300-ohm resistor, and 50 hertz is the lowest frequency to be amplified. From the above rule, the capacitive reactance should be 1/10 of 300, or 30 ohms, at 50 Hz. Using the equation for capacitance reactance:

$$X_c = \frac{1}{2\pi fC}$$

The following Practice Exercise questions cover the subjects which you have just studied. They are:

VOLTAGE AMPLIFIERS

POWER AMPLIFIERS

AMPLIFIER CLASSIFICATION

CLASS A AMPLIFIERS

CLASS B AMPLIFIERS

CLASS AB AMPLIFIERS

1. What is the formula for the voltage gain of a voltage amplifier?
2. Assume that an amplifier has an input signal of 1.5 volts and an output signal of 30 volts. What is the voltage gain?
3. What is the voltage gain of a vacuum tube amplifier if $\mu = 100$, $r_p = 35 \text{ k}\Omega$ and $R_L = 100 \text{ k}\Omega$?
4. What is the difference between a voltage amplifier and a power amplifier?
5. What is the difference between a Class A, a Class B and a Class C amplifier?
6. In a Class A amplifier, what two factors determine whether the operation is on the linear portion of the characteristic curve?
7. In a Class A amplifier, if the bias voltage is increased (more negative), will the positive or negative alternation of the plate current signal be distorted?
8. What is the meaning of the term "efficiency" with regard to an amplifier?
9. What is the efficiency of a Class A amplifier?
10. With respect to the tube's characteristics, where is the bias point set for Class B operation?

11. Can a Class B amplifier handle a larger signal than a similar Class A amplifier?
12. What is the approximate efficiency of a Class B amplifier?
13. What is a Class AB amplifier?
14. Would a Class AB₂ amplifier draw grid current?

and rearranging the terms by first multiplying both sides by C:

$$CX_c = \frac{C}{2\pi fC}$$

Since $\frac{C}{C} = 1$, the equation reduces to:

$$CX_c = \frac{1}{2\pi f}$$

Next, divide both sides by X_c :

$$\frac{CX_c}{X_c} = \frac{1}{2\pi f} \div X_c$$

Since $\frac{X_c}{X_c} = 1$, the equation reduces to:

$$C = \frac{1}{2\pi f} \div X_c = \frac{1}{2\pi f} \times \frac{1}{X_c}$$

$$C = \frac{1}{2\pi f X_c}$$

Substituting the values in the example:

$$C = \frac{1}{6.28 \times 5 \times 10^1 \times 3 \times 10^1}$$

$$= \frac{1}{94.2 \times 10^2}$$

$$= \frac{1}{9.42 \times 10^3}$$

$$= .106 \times 10^{-3} = 106 \mu\text{F}.$$

For low-frequency amplifiers, cathode bypass capacitors are usually of the electrolytic type to obtain the required high values. However, since the bias developed across the resistor is usually low, the voltage rating of this capacitor is only 10 to 50 volts and its physical size is small.

Cathode bias is usually found in Class A or Class AB amplifiers. Sometimes cathode bias is employed in addition to fixed bias in Class B and Class C amplifiers.

Grid-Leak Bias

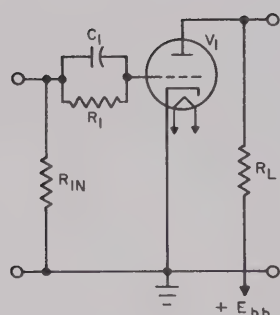


Figure 7

With the self-bias method known as **GRID-LEAK BIAS**, the dc bias is developed as a result of the leakage or discharge of a capacitor through a resistor. A typical grid-leak bias circuit arrangement is shown in Figure 7. A parallel RC combination is connected in series with the grid circuit of V_1 .

This type of bias is normally used with circuits that have a continuous ac input signal, such as oscillators. The positive alternations of the input signal cause V_1 to draw grid current. However, the resistance of R_1 and R_{IN} is quite high, and the amount of grid current is therefore limited to a small amount which cannot damage the tube. This "leakage" current from the grid, through R_1 and R_{IN} to ground, causes a voltage drop across the resistors that charges C_1 , placing a negative potential on the grid. This negative potential is the bias voltage.

To keep a fairly constant voltage across R_1 , the value of C_1 is chosen so that it charges quickly when grid current is drawn, and because the resistance of R_1 is large, the C_1 charge leaks off slowly. Grid-leak bias is seldom used in Class A, AB or B amplifiers because the signal becomes distorted when grid current is drawn.

Negative-Leg Bias

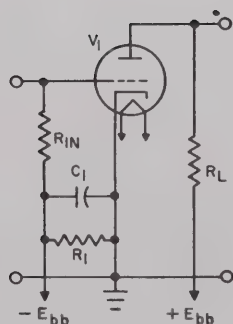


Figure 8

A combination of self- and fixed bias called **NEGATIVE-LEG BIAS** is shown in Figure 8. Plate current from $-E_{bb}$ through R_1 , V_1 , R_L and $+E_{bb}$ develops a voltage across R_1 which makes its left end negative with respect to the V_1 cathode. Because R_{IN} connects to the negative end of R_1 , the control grid of V_1 is also negative with respect to the cathode. R_1 is bypassed by C_1 to prevent voltage variations across it.

If additional amplifier stages are connected to the same power supply (plates to $+E_{bb}$ and cathodes to ground), their plate currents will also flow through R_1 . This requires that all plate currents be considered when calculating values of R_1 for a specific bias.

Contact Bias

Another bias method in common use is shown in Figure 9. As electrons pass from the cathode to the plate, a few strike the grid and pass down through resistor R_{IN} to the cathode. This makes the end of R_{IN} connected to the grid negative with respect to the cathode. Since this grid current is very small, R_{IN} must have a very high resistance (on the order of 10-M Ω) to produce a one- or two-volt drop. Consequently, this bias method is only practical when very small input signal voltages are to be applied to the grid.

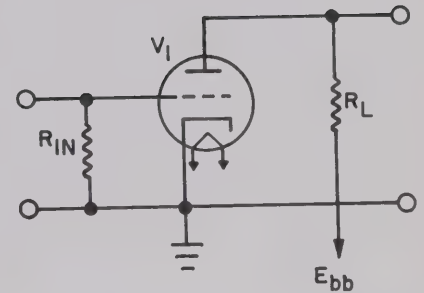
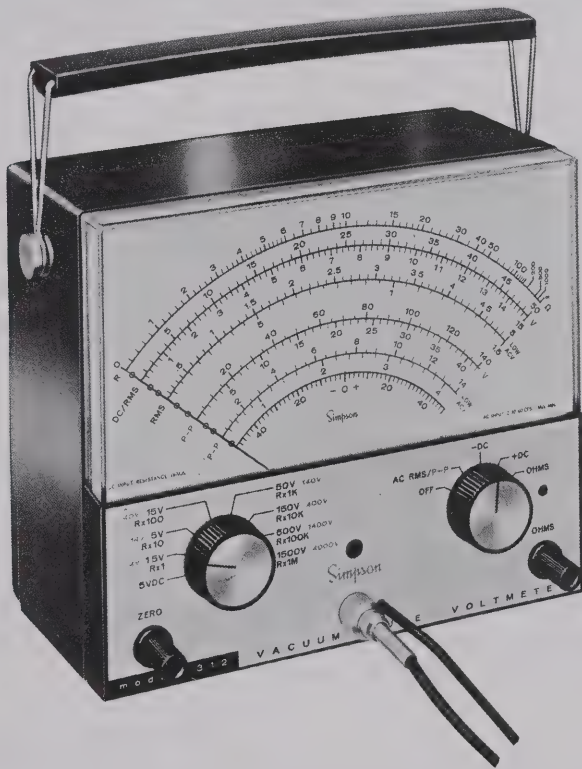


Figure 9



Measurement of bias in high-impedance grid circuits must be performed using a high-impedance meter to prevent circuit loading.

Courtesy Simpson Electric Co.

Because the grid and cathode of a tube must be made of different materials to obtain a high electron emission from the cathode and a very low electron emission from the grid, a difference of potential exists between them. Called the "CONTACT DIFFERENCE OF POTENTIAL," this voltage aids the

electrons emitted from the cathode in reaching the grid, thus making grid current possible. For this reason, the resulting voltage drop across R_{IN} is referred to as **CONTACT BIAS**.

CALCULATING THE CATHODE BIAS RESISTANCE

The resistance value for the cathode bias resistor can be obtained by dividing the required bias voltage by the no-signal cathode current. The no-signal cathode current is equal to the plate current in the case of a triode, or the sum of the plate and screen currents, in the case of a tetrode or pentode. In equation form:

$$R = \frac{E_c}{I_b + I_{c2}}$$

where: E_c is the required dc grid bias in volts,

I_b is the no-signal plate current in amperes,

I_{c2} is the screen current in amperes, and

R is the resistance of the cathode bias resistor in ohms.

As an example, assume that you want to determine the resistance of a cathode bias resistor for a type 6CB6 pentode, when the plate current is 9.5 mA, the screen current is 2.8 mA, and the required grid voltage for linear Class A operation is 2.2 volts. Using the equation:

$$\begin{aligned} R &= \frac{E_c}{I_b + I_{c2}} \\ &= \frac{2.2}{.0095 + .0028} \\ &= \frac{2.2}{.0123} \\ &= 178.9 \text{ ohms.} \end{aligned}$$

In a circuit where negative-leg bias is employed, it is necessary to determine the total plate and screen grid currents of all tubes in series with the bias resistance. Then the resistance can be found by dividing the desired voltage by this total current, as previously done for cathode bias.

FREQUENCY RESPONSE

An important characteristic of a low-frequency amplifier is its ability to provide equal amplification for all frequencies of its intended application. The frequency range over which an amplifier provides nearly equal amplification is called its **FREQUENCY RESPONSE**. An amplifier's specified frequency response is the band of frequencies over which the amplifier provides no less than half the required output.

An example frequency response specification is that of a high-quality high-fidelity twenty-watt audio amplifier, whose response covers the range of frequencies from 10 Hz to 40 kHz. This specification means that, with the proper input signal, the amplifier's output will be no less than ten watts over the frequency range of 10 Hz to 40 kHz. In practice, a typical amplifier having this specification will usually provide about ten watts output at 10 Hz, rise to twenty watts output from 20 Hz to 20 kHz, and drop back down to ten watts at 40 kHz.

TYPES OF COUPLING

The method of connecting or coupling one amplifier stage to another for cascade operation is quite important. Three basic methods used in low-frequency amplifiers are: (1) resistance coupling, (2) impedance coupling and (3) transformer coupling.

Resistance Coupling

Figure 10 shows a **RESISTANCE COUPLING** arrangement, sometimes known as **RESISTANCE-CAPACITANCE (RC) COUPLING**. This coupling arrangement between the stages consists of resistor R_3 and capacitor C_2 .

Capacitor C_2 has two distinct functions: (1) to block the positive dc plate voltage of tube V_1 from the grid of tube V_2 and (2) to transfer the amplified ac signal from the plate of V_1 to the grid of V_2 .

With no input signal voltage applied, electrons flow from ground through R_1 , V_1 and back to $+E_{bb}$ through R_2 . There is also an ac path from ground

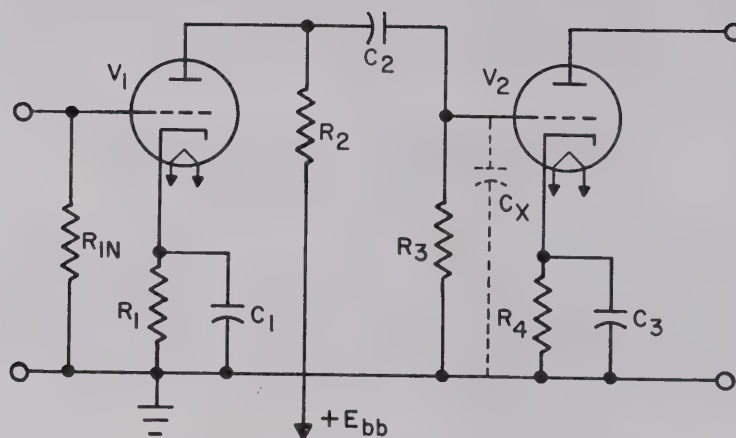


Figure 10

through R_3 , C_2 and R_2 to $+E_{bb}$. Although there is no continuous current in this path, electrons flow from ground through R_3 until C_2 is charged. While C_2 is charging, electrons leave C_2 and flow, along with the V_1 plate current, through R_2 to $+E_{bb}$.

Capacitor C_1 is charged to the voltage across R_1 , since it is in parallel with R_1 . Capacitor C_2 is charged to the plate supply voltage minus the drop across the plate load resistor, R_2 . For example, if the plate supply voltage is 280 volts and a voltage drop of 80 volts exists across R_2 , then the dc voltage across C_2 is $280 - 80$, or 200 volts. After capacitor C_2 is fully charged, there is no more current through R_3 , and the voltage across R_3 drops to zero. R_3 is the grid resistor of tube V_2 .

Assume that the signal voltage across R_{IN} drives the grid of V_1 less negative and causes an increase of plate current. With an increase of plate current, the voltage drops across R_1 and R_2 also increase. However, the action of capacitor C_1 tends to prevent a change of voltage across R_1 . The increased voltage drop across R_2 reduces the plate voltage of V_1 and changes the voltage across C_2 .

In this example, if the voltage drop across R_2 increases to 100 volts, the voltage across capacitor C_2 must reduce to 180 volts ($280 - 100$ volts). With reduced voltage across it, C_2 starts to discharge. The path of the discharge current is down through R_3 to ground, up through R_1 , through V_1 from cathode to plate and back to C_2 . This discharge current causes a voltage drop across R_3 which makes the grid of V_2 negative with respect to its cathode.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

GRID BIAS METHODS

SEPARATE SUPPLY

CATHODE BIAS

GRID-LEAK BIAS

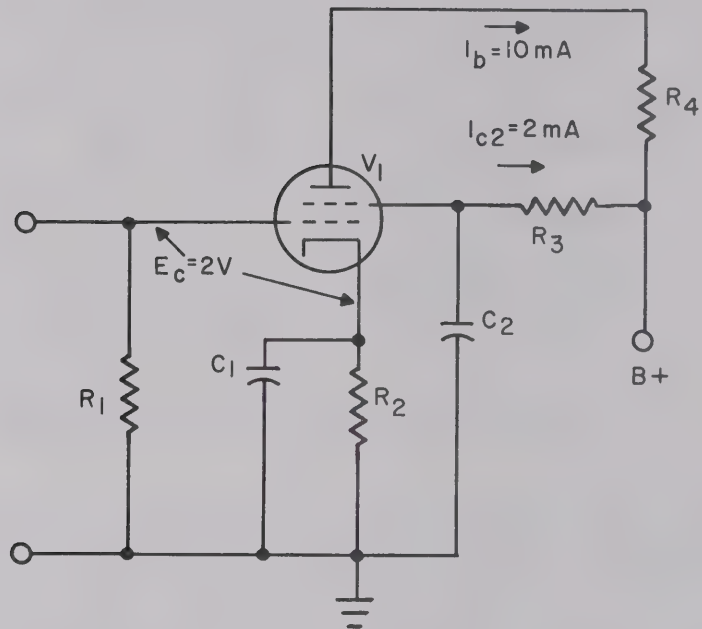
NEGATIVE-LEG BIAS

CONTACT BIAS

CALCULATING THE CATHODE BIAS RESISTANCE

15. The grid bias arrangement of Figure 5 is referred to as _____ bias.
16. Would fixed bias be normally used in a Class A amplifier?
17. How does the cathode bias arrangement of Figure 6 develop a negative grid bias voltage?
18. What is the purpose of C_1 in Figure 6?
19. For proper operation, the R_1C_1 time constant should be _____.
20. If an amplifier has a cathode bias resistor with a value of 250 ohms, what should be the reactance of the bypass capacitor at the lowest frequency to be amplified?
21. Explain how the circuit of Figure 7 develops the bias voltage.
22. Contact potential bias requires a high value of grid load resistance. True or False?

23. What is the value of R_2 required in this circuit to develop the value of grid bias shown?



24. If the lowest frequency to be amplified by the circuit of the previous exercise is 100 Hz, what is the value of C_1 ?

When the input signal voltage makes the grid of V_1 become more negative with respect to its cathode, its plate current is reduced. With less plate current, the voltage drops across R_1 and R_2 are reduced. Again, the action of C_1 tends to maintain a constant voltage across R_1 , but the reduction of voltage across R_2 allows an increase of voltage at the plate of V_1 .

With the voltage at the plate of V_1 increased, capacitor C_2 charges. Electrons flow from ground through R_3 until C_2 is charged. This charge current causes a voltage drop across R_3 which makes the grid of V_2 less negative with respect to its cathode. By causing capacitor C_2 to charge and discharge, the ac component of the plate current in V_1 develops an ac voltage across R_3 and the grid-cathode circuit of V_2 .

It is good design practice to make the resistance of plate resistor R_2 fairly high. In fact, it is usually from 1 to 10 times the value of the plate resistance. Capacitor C_2 must have sufficient dielectric strength to prevent a voltage breakdown which would allow the dc plate voltage of V_1 to reach the grid of V_2 .

The reactance of the coupling capacitor, C_2 , at the lowest signal frequency, should be low compared to the resistance of grid load resistor R_3 . In effect, C_2 and R_3 form a high-pass filter with the drop across R_3 as the output voltage. Therefore, the time constant must be large to prevent excessive attenuation of the lower frequencies. If the value of the coupling capacitor is too small, its reactance will be high, causing a reduction of low-frequency signal voltage for the following grid circuit.

To determine the value of the coupling capacitor, it is common practice to assume a time constant of .004 second and a frequency of 100 Hz for audio amplifiers. Under these conditions, with a grid load of 100,000 ohms, or .1 megohm, the coupling capacitance can be calculated by the following equation:

$$T = RC,$$

where: T is time in seconds,

C is the coupling capacitance in microfarads, and

R is the grid load resistance in ohms.

Dividing both sides by R , an equation for determining the value of coupling capacitance is obtained:

$$\frac{T}{R} = \frac{RC}{R}$$

VACUUM TUBE LOW-FREQUENCY AMPLIFIERS

Since $R/R = 1$, the equation reduces to:

$$C = T/R.$$

Substituting the values of T and R, we now obtain the value for C:

$$\begin{aligned} C &= \frac{4 \times 10^{-3}}{1 \times 10^5} \\ &= 4 \times 10^{-8} \\ &= .04 \mu\text{F}. \end{aligned}$$

At a frequency of 100 Hz:

$$\begin{aligned} X_c &= \frac{1}{2\pi fC} \\ &= \frac{1}{6.28 \times 1 \times 10^2 \times 4 \times 10^{-8}} \\ &= \frac{1}{25.12 \times 10^{-6}} \\ &= 3.99 \times 10^4 \\ &= 39,900 \text{ ohms}. \end{aligned}$$

For better low-frequency gain, the time constant is increased to .01 second.
Therefore:

$$C = T/R = \frac{.01}{.1} = .1 \mu\text{F},$$

and at a frequency of 100 Hz:

$$X_c = 15,900 \text{ ohms}.$$

Since the reactance of the coupling capacitor decreases as the signal frequency increases, the coupling capacitor has little effect on the high-frequency response of the amplifier. The rapid dropoff in high-frequency re-

sponse is due to the shunting effects of C_x , shown in Figure 10. C_x is composed of the effective input capacitance of V_2 , the plate-cathode capacitance of V_1 , and the various stray wiring capacitances.

As the signal frequency increases, the reactance of C_x decreases. Since C_x and R_3 are in parallel, their total impedance to the input signal decreases as the signal frequency increases. With a decrease in impedance of R_3 and C_x , more of the signal voltage appears across C_2 and less across R_3 and C_x . This results in a decrease in the signal on the grid of V_2 , which results in a reduction of the gain of the amplifier.

Resistance coupling is employed whenever a relatively constant frequency response is desired and weight and cost must be held to a minimum. The disadvantage of resistance coupling is that there is a dc voltage drop across the plate load resistor. This voltage drop causes a loss of power supply energy, resulting in decreased amplifier efficiency.

Impedance Coupling

In the circuit of Figure 11, inductor L_1 replaces resistor R_2 of Figure 10. Inductor L_1 , along with coupling capacitor C_2 and grid resistor R_2 , form what is known as an **IMPEDANCE-COUPLED** amplifier. The inductor is made of a large number of turns of wire wound on an iron core. Due to its self-inductance, the coil presents a high reactance to low-frequency variations of plate current, but has a fairly low resistance to direct current.

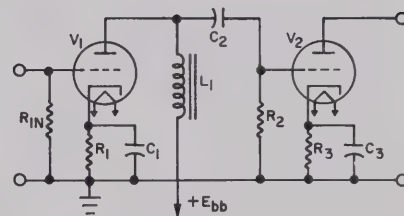


Figure
11

In general, the action of impedance coupling is similar to resistance coupling; however, the lower dc resistance of the inductor causes a smaller loss of power supply energy. Since the reactance of inductor L_1 varies with frequency, the voltage developed across it also varies with changes of frequency. Therefore, the response of the impedance-coupling circuit is not uniform over the entire operating frequency range. Unless the reactance of the inductor is large at the lowest frequencies, the low frequencies are attenuated.

Increasing the number of turns of the winding of an inductor increases the distributed capacitance between the adjacent turns. The adjacent turns act like plates of small capacitors, and therefore, the more turns in the inductor coil, the greater the number of small capacitors.

These capacitors are effectively in parallel with the inductor, and they form a parallel LC circuit. At the resonant frequency of this circuit, its parallel

impedance is high and the resulting signal voltage applied to the grid of the next stage (V_2 in Figure 11) is large.

The change of load impedance with frequency causes an uneven frequency response, with the output highest at the circuit's resonant frequency. Above the resonant frequency of the circuit, the distributed capacitance has decreased reactance and the output voltage decreases, as a result of the shunting effect of the distributed capacitance.

Transformer Coupling

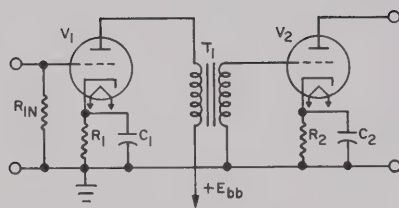


Figure
12

Figure 12 shows a **TRANSFORMER-COUPLED** amplifier arrangement using an iron core transformer, T_1 . The transformer primary is in series with the plate circuit of tube V_1 , while the secondary is in the grid circuit of tube V_2 . Changes in the primary voltage induce changes of voltage in the secondary. In addition to the amplifying action of the tubes, the transformer can step up the signal voltage in proportion to the turns ratio of the windings. For example, if the turns ratio is 3-to-1 step-up, the secondary signal voltage is three times the primary signal voltage.

There is a limit to the number of times a transformer can step-up the signal voltage. Practical considerations normally keep the step-up ratio relatively low. The transformer primary winding has inductive reactance which varies directly with frequency, and to provide the necessary reactance at low frequencies, the primary must be wound with a comparatively large number of turns, just as was required for inductor L_1 in Figure 11.

To obtain a step-up ratio, the secondary winding must have more turns than the primary. But, as turns are added, the distributed capacitance between the adjacent turns and the various layers increases. This increase in distributed capacitance affects the frequency response exactly as explained for the impedance-coupled amplifier of Figure 11.

Thus, the number of primary turns must be sufficient to provide proper reactance at low frequencies, while the number of secondary turns must be limited to keep the shunting effect of the distributed capacitance low at the higher frequencies. To satisfy both requirements, the transformer turns ratio seldom exceeds a 3-to-1 step-up.

Transformer coupling is used in many Class B amplifiers because grid current is drawn. With a transformer, the high impedance of the preceding stage can be matched to the low-impedance grid circuit required for a Class B stage.

PARALLEL AMPLIFIERS

The power available from a particular tube is limited. Too large a signal drives the grid positive and, if the bias is increased, distortion is caused by operation on the nonlinear portion of the tube's curve. One way to increase the power output of a stage without causing distortion is to employ two or more tubes in **PARALLEL OPERATION**. For this arrangement, the grids, plates and cathodes of the tubes are tied together.

The signal power delivered by a tube is determined by the current variation in the plate circuit. For two tubes in parallel, the output is twice that of one tube because the plate current of both tubes flows through the load. Therefore, for the same grid and plate voltages, the output has twice the power with no increase in distortion.

PUSH-PULL AMPLIFIERS

Another method for increasing power output without increasing distortion is the use of a **PUSH-PULL AMPLIFIER** stage, such as the one shown in Figure 13. The plate circuit of V_1 is like that of tube V_1 in Figure 12. However, in Figure 13, the secondary of transformer T_1 is center-tapped, with the upper end of T_1 connected to the grid of tube V_2 , and the lower end connected to the grid of tube V_3 . The grid circuits of tubes V_2 and V_3 are completed through the transformer center tap, resistor R_2 , and their respective cathodes.

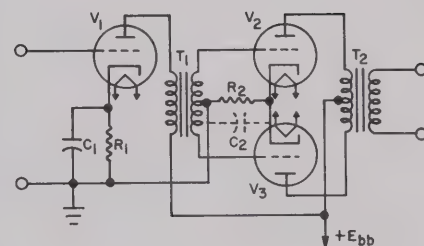


Figure
13

A change of plate current in the primary of transformer T_1 induces a secondary voltage which, with respect to the center tap, causes one end of the winding to become positive and the other negative. The center tap is connected to the ground, or zero potential point, and the ends of the secondary are of opposite polarity, or 180° apart in phase.

The source of grid bias for tubes V_2 and V_3 is the voltage drop across resistor R_2 . The plate current for tubes V_2 and V_3 also flows through R_2 . The series grid-cathode circuit for V_2 consists of the top half of the T_1 secondary and R_2 . The series grid-cathode circuit for V_3 consists of the bottom half of the T_1 secondary and R_2 . The signal voltage in each grid circuit is in series with the bias.

As the upper end of the T_1 secondary becomes positive, the signal voltage opposes the bias, the grid of V_2 becomes less negative, and V_2 plate current

increases. Simultaneously, the lower end of the T_1 secondary becomes negative, the signal voltage aids the bias, the grid of V_3 becomes more negative, and V_3 plate current decreases. Because the plate current of one tube increases as the plate current of the other tube decreases, the total current carried by R_2 remains almost constant.

The path of V_2 plate current is from ground through R_2 , from cathode to plate through the tube, and through the top half of the T_2 primary to $+E_{bb}$. For V_3 , the plate current path is from ground through R_2 , from cathode to plate, and through the bottom half of the T_2 primary to $+E_{bb}$.

Since the primary of T_2 is one continuous winding, the plate currents are in opposite directions and, therefore, set up opposing magnetic fields. The magnetic field set up around any given coil varies with the current in it. However, in this case, when the plate currents are equal, the opposing fields also are equal and neutralize each other. Therefore, the total magnetic flux is zero when both tubes are conducting equally.

During one half-cycle of a signal voltage applied to the grid circuit of tube V_1 , the plate current of V_2 increases and the plate current of V_3 decreases. During the next half-cycle of the input signal, V_2 plate current decreases and V_3 plate current increases. Due to these changes of plate current, the strength of the magnetic field around one half of the T_2 primary increases, while the magnetic field around the other half of the T_2 primary decreases. As the fields combine, the total T_2 primary winding flux equals the difference between the two opposing fields. Remember that the opposite changes of the two fields cause the variations of total flux to be twice as great as the change in either field alone.

The output signal obtained from the resultant flux field is twice as large as the output obtained from a single tube. Class A push-pull operation is most often used for keeping distortion low. This circuit arrangement tends to cancel any out-of-phase signal distortion components that might be generated in an amplifier stage.

CLASS B PUSH-PULL AMPLIFICATION

To obtain greater output from a push-pull stage, it can be operated as a Class B amplifier. However, if the tubes are biased at the actual plate current cutoff, Class B operation becomes unsatisfactory for an audio amplifier or

for many other low-frequency applications because of the highly distorted output signal.

To obtain linear operation from push-pull Class B amplifiers, they are operated as shown in Figure 14. Here, the negative grid bias is slightly less than cutoff so that a linear composite curve is obtained. Because the nonlinear portions of the V_2 and V_3 tube curves are equal and opposite in curvature, a linear curve is attained for the output current, I_z .

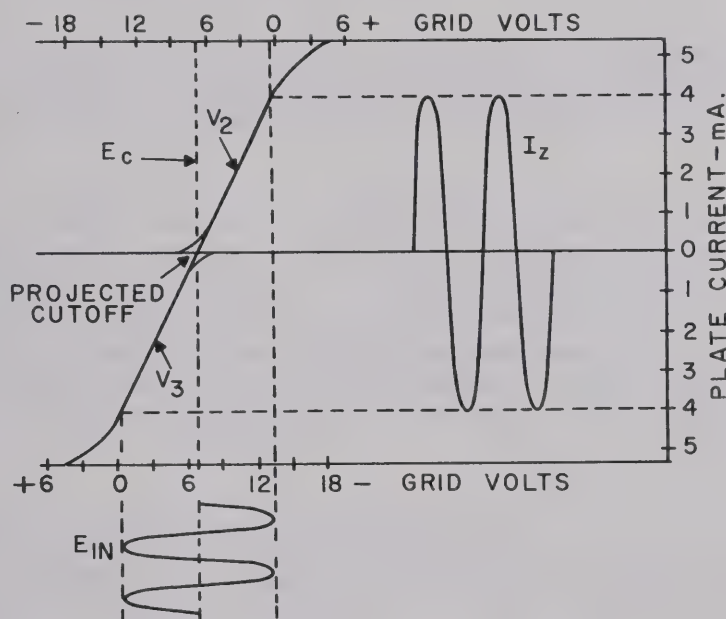


Figure 14

E_{IN} is the signal in the primary winding of T_1 of Figure 13. V_2 conducts more when E_{IN} causes the signal in the top T_1 secondary to swing positive with respect to the center tap. At the same time, the input signal to V_3 swings negative with respect to the T_1 primary center tap, which reduces the already small output current of V_3 to zero. The positive-going signal to V_2 drives the V_2 grid from its no-signal point of -7 volts up to just under zero volts. This causes V_2 to conduct heavily, and I_z increases to 4 mA. When E_{IN} reduces to zero, the V_2 grid signal falls back to -7 volts and I_z drops to zero.

E_{IN} now causes the signal to V_2 to go more negative, and at the same time, the signal to V_3 increases from below -7 volts up to a little below zero

volts. This causes the V_3 plate current to increase, which results in an increase in I_z to 4 mA. However, I_z has increased in the opposite direction. Remember that I_z is the total output current through the T_2 primary, which is the plate load for both V_2 and V_3 . Because the current, I_z , represents alternate increases in current from each half of the T_2 primary windings, the output from the T_2 secondary winding is developed from the combined V_2 and V_3 changes in plate current represented by I_z . This results in an output signal that is much larger than the input. For a power amplifier, the input signals to V_2 and V_3 may vary by only a few mA, but the resultant changes in current in the T_2 primary can vary up to several hundred mA.

The operating point is located where the composite curve crosses the zero plate current line. The grid voltage required to obtain this operating point is referred to as the **PROJECTED CUTOFF BIAS** (E_c) of the tube.

The projected cutoff bias shown in Figure 14 is 7 volts negative. With a 7-volt peak input signal, the waveform of the plate current (as shown by the I_z curve at the right of Figure 14) becomes an almost exact replica of that of the input signal voltage. Compared with the Class A operation of Figure 13, much larger input signals can be applied to the grids without driving them positive. An output with low distortion and a large current swing for large signal power can be obtained by operating on the linear composite curve.

With Class B operation, much larger plate voltages may be applied without exceeding the plate dissipation, thereby making possible larger signal power output.

To ensure a smooth transition of output signal from one push-pull tube to the other, they are usually operated a little above cutoff, or between Class A and B. As explained earlier, this is called Class AB operation.

AMPLIFICATION REQUIREMENTS

The main purpose of an amplifier is to increase the magnitude of its input signal voltage or power. However, in doing this task it is often important that certain waveform characteristics which occur are retained as the signal is amplified. It is good economy and common sense to build a low-frequency amplifier with the minimum number of components necessary to produce the desired quality of amplification. For many purposes the requirements are simple, and the circuit components either couple the signal from one tube to another or supply the correct voltages to each tube electrode.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

FREQUENCY RESPONSE

TYPES OF COUPLING

RESISTANCE COUPLING

IMPEDANCE COUPLING

TRANSFORMER COUPLING

PARALLEL AMPLIFIERS

PUSH-PULL AMPLIFIERS

CLASS B PUSH-PULL AMPLIFICATION

25. What are the two functions of the coupling capacitor in an RC coupling circuit?
26. Briefly, how does the coupling capacitor in an RC coupling arrangement transfer the ac signal from the plate of one tube to the grid of the next?
27. What components in the circuit of Figure 10 determine the low-frequency response and the high-frequency response?
28. For a good low-frequency response, the R_3C_2 time constant in the circuit of Figure 10 should be _____.
29. How does an impedance-coupled amplifier differ from an RC coupled amplifier?
30. What is the maximum turns ratio for a transformer used in a transformer-coupled amplifier?
31. Transformer coupling is often used for Class _____ amplifiers.
32. How does the power output for a parallel amplifier compare to that of a single tube stage?
33. What is the phase relation of the grid signals for the two tubes in a push-pull amplifier?

34. The total magnetic flux is zero in the plate transformer of a push-pull amplifier under no-signal conditions. True or False?
35. Does push-pull operation increase or decrease distortion?
36. Is the peak-to-peak output developed by a push-pull amplifier greater than that developed by a parallel amplifier?
37. In a Class B push-pull amplifier, are the tubes operated exactly at cutoff?

For other applications, rather exact characteristics are specified. Additional components must therefore be added to the basic circuit to change its characteristics to those required. To explain the purpose of these additions, it is necessary to describe some of the important signal characteristics that must be preserved by these amplifiers.

HARMONICS

Musical instruments produce sounds by means of a vibrating element, such as a reed or string, which sets up sound waves in the surrounding air. These sounds (called notes or tones) have frequencies that are the same as the vibrating element which produced them. However, when played on different instruments such as a piano and violin, notes of the same "pitch," or frequency, do not sound the same.

Experiments have shown that differences in sounds of the same frequency are due to the number and magnitude of OVERTONES that are generated. In electronics, the basic frequency of a tone is called the **FUNDAMENTAL**. The overtones, or **HARMONICS**, have frequencies that are equal to whole number multiples of the fundamental frequency. The fundamental is considered to be the "first harmonic."

Thus, the "second harmonic" has twice the frequency of the fundamental, or "first harmonic." Three times the fundamental frequency is the third harmonic, and so on. For example, frequencies of 1000, 1500, 2000 and 2500 Hz are the 2nd, 3rd, 4th and 5th harmonics of a 500-Hz fundamental.

Whenever two or more sinewaves of different frequencies are added, the resulting wave no longer is shaped like a sinewave. This is shown by the curves in Figures 15 and 16, where the sinewaves are dashed lines and the resultant wave is a solid line. In each case, the resultant wave does not resemble either of the original sinewave curves.

Figure 15A shows the combination of a fundamental and its second harmonic. Notice that the amplitude of the harmonic is lower than that of the fundamental. The second harmonic completes one cycle in the same time that the fundamental completes one-half of a cycle.

The resultant curve is plotted by taking the algebraic sum of corresponding points on the two sinewaves. For example, at position A in Figure 15A, the amplitude of the second harmonic is zero. The resultant amplitude is

VACUUM TUBE LOW-FREQUENCY AMPLIFIERS

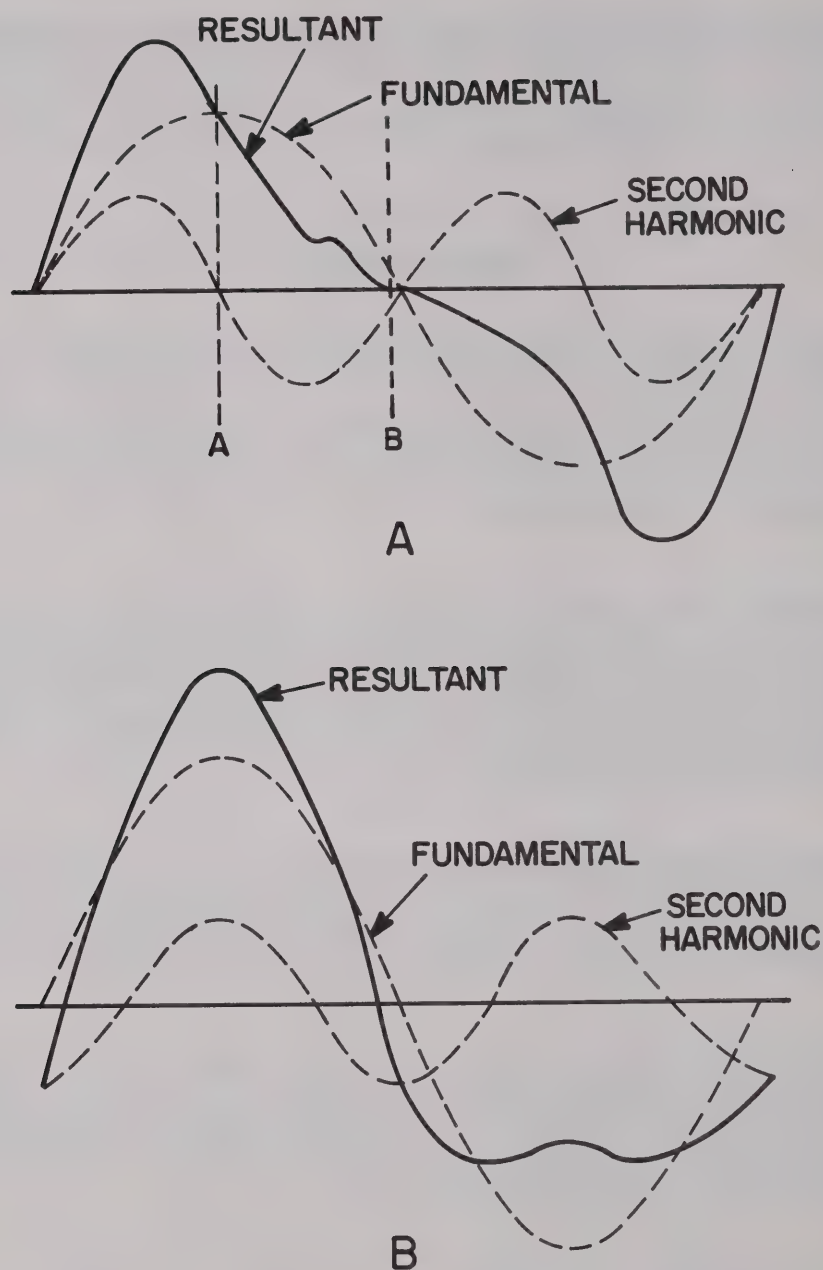


Figure 15

equal to the fundamental. At position B, the amplitudes of the fundamental and harmonic are equal but opposite in phase, and the resultant amplitude is zero. If the amplitude of either wave is changed, the resultant waveshape will also change.

Another method of changing the shape of the resultant wave is accomplished by shifting the phase of the harmonic with respect to the fundamental. This condition is shown in Figure 15B, where the second harmonic is phase shifted 45° with respect to the fundamental. The resultant wave is very different from that of Figure 15A. On the positive alternation of the fundamental, the fundamental and second harmonic add, producing a resultant amplitude which is larger than the fundamental. On the negative alternation of the fundamental, the fundamental and second harmonic oppose, producing a resultant amplitude which is less than that of the fundamental.

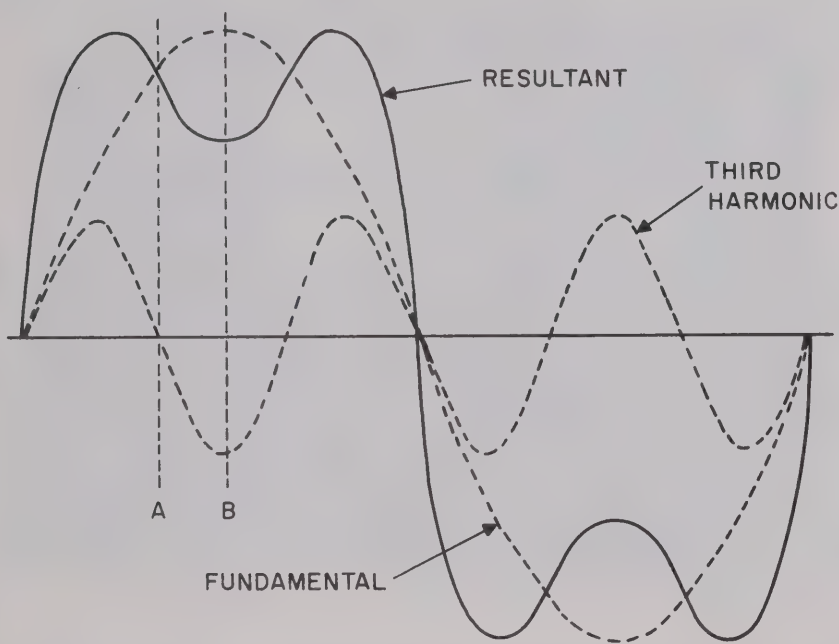


Figure 16

The third harmonic and the fundamental produce the waveform of Figure 16. In the same manner, higher harmonics can be added to the fundamental to produce various resultants.

Several harmonics can be combined simultaneously with the fundamental to produce a very complex waveshape. It has been found that alternating current waves, regardless of shape, are composed of a fundamental and a number of harmonics. Each harmonic has a specific amplitude and phase relationship in respect to the fundamental. The shape of any wave can be varied by adding or subtracting harmonics, or by varying the amplitudes or phases of the harmonics that are present.

Some waveshapes contain only even or only odd harmonics. Other waveshapes contain both even and odd harmonics. When an ac wave contains high-amplitude odd harmonics, its positive and negative alternations will be symmetrical (have the same shapes). When an ac wave contains high-amplitude even harmonics, its positive and negative alternations will not be symmetrical.

Since a single-tube amplifier operating Class B or AB generates even harmonics, its output waveshape is distorted. A relatively symmetrical output waveform can be obtained by using a push-pull Class B or AB stage. The outputs of the push-pull stage combine so that the even harmonics generated by the stage are canceled. As a result, a more symmetrical waveform appears at the push-pull stage output.

TYPES OF DISTORTION

One major type of distortion, called **HARMONIC DISTORTION** or **AMPLITUDE DISTORTION**, is caused by the generation of harmonics in the amplifier tube. If a Class A amplifier is operated on the linear portion of the I_b - E_c tube characteristic curve, very few of the undesirable harmonics are generated, and therefore, minimum distortion results. In contrast, when a Class A amplifier is operated over a nonlinear portion of the I_b - E_c curve, the output is not an exact replica of the input voltage. Instead, part of the negative alternation of the input signal causes the tube to operate on the lower nonlinear portion of the curve. The resulting distortion of the plate current waveform introduces new harmonics into the signal. The effect is somewhat like the flattened negative alternation of Figure 15B.

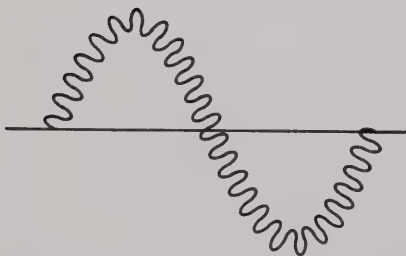


Figure
17

INTERMODULATION (IM) DISTORTION is a form of amplitude distortion which may occur when more than one signal frequency is applied to the input of an amplifier. One type of intermodulation distortion occurs when two input frequencies are mixed together so that the higher frequency "rides on" the waveform of the lower frequency, as shown in Figure 17. Another type of intermodulation distortion is the generation of the sum and difference frequencies from the input frequencies, as explained in the following example. If we apply 50-Hz and 3000-Hz signals to the input of an amplifier that produces intermodulation distortion, the amplifier output would contain the amplified original frequencies (50 Hz and 3000 Hz), along with their sum ($3000 \text{ Hz} + 50 \text{ Hz} = 3050 \text{ Hz}$) and difference ($3000 \text{ Hz} - 50 \text{ Hz} = 2950 \text{ Hz}$) frequencies. The amount, or percent, of IM distortion depends primarily on signal amplitude and how well the amplifier is designed. A typical audio amplifier normally has many different frequency signals simultaneously applied to its input. If intermodulation distortion were not kept to a minimum, reproduction of music would be extremely unpleasant.

Another type of distortion, called **FREQUENCY DISTORTION**, may occur when some harmonics in the input signal are amplified a great deal more than others.

Another type of distortion, called **PHASE DISTORTION**, may occur when the phase of some of the harmonics in the output differs from the phase of the harmonics at the input. If the phase shift of all of the harmonics is proportional to their frequency, no distortion results.



This instrument is designed to measure the intermodulation distortion in an amplifier.

Courtesy Heath Co.

INVERSE FEEDBACK

Remember that, when the signal voltage drives the grid of a vacuum tube less negative (more positive), the plate current increases. Conversely, when the signal voltage drives the grid of a vacuum tube less positive (more negative), the plate current decreases.

With no input signal applied to a typical amplifier circuit, some definite level of plate current is carried by the plate load resistor and cathode

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resistor. This current causes a voltage drop across each of these resistors. The voltage drop across the cathode resistor may be held almost constant by the action of a cathode bypass capacitor. These components provide the necessary self- (cathode) bias.

With no signal, the plate current does not vary and there is a fixed voltage drop across the tube between plate and cathode. When the signal voltage drives the grid in the positive direction (less negative), the tube becomes more conductive and the plate current increases. The higher plate current increases the voltage drop across load resistor R_L , but due to its greater conductivity, the voltage drop between the plate and cathode (within the tube) decreases. Thus, compared with the no-signal condition, as the grid becomes more positive, the plate becomes less positive, or more negative, and this change is coupled by a capacitor to the grid of the next stage.

The reverse action also occurs. As the signal drives the grid more negative, the plate current decreases, the drop across the load resistor decreases, and the drop between the plate and cathode of the tube increases. Thus, compared with the no-signal condition, as the grid becomes more negative, the plate becomes more positive. A change of signal voltage causes the grid and plate signal to vary in opposite directions, so that they are 180° out-of-phase.

When a number of stages are connected in cascade, this phase reversal occurs in each succeeding stage. In a two-stage circuit, the output signal voltage of the second stage is in phase with the input signal voltage of the first stage. In a three-stage circuit, the output signal voltage is again 180° out-of-phase with the input. As a general rule for resistance-coupled amplifiers, with an odd number of stages, the input and output voltages are 180° out-of-phase, and with an even number of stages, the input and output signal voltages are in phase.

A portion of the output voltage may be applied back to the input. This process is known as **FEEDBACK**. If the feedback is in phase with the input signal, it causes an increase of input voltage, resulting in an even higher output. This "building up" process is known as **REGENERATIVE FEEDBACK**. If the feedback is 180° out-of-phase, it partly neutralizes the input voltage and causes a reduction of output. This reducing action is called **DEGENERATIVE FEEDBACK** or **INVERSE FEEDBACK**.

The interelectrode capacitance between the plate and grid of a triode tube causes some of the variations of voltage on the plate to be coupled back to the grid. In many cases this internal feedback is undesirable. Tetrode and pentode type tubes were developed to overcome this undesirable internal feedback.

However, both types of feedback do have certain advantages which find practical application. With regenerative feedback the in-phase voltage adds to the signal voltage at the grid and is amplified by the tube circuit. Larger voltage variations at the plate result in greater feedback which is amplified further. This building-up process would continue indefinitely except for the limiting action of the tube and its associated circuits.

A common application of regenerative feedback is in regenerative amplifiers. In this type of amplifier, a small amount of regenerative feedback is applied to the amplifier. This causes a large increase in amplifier gain.

Very often, sufficient regenerative feedback is developed to cause the amplifier to generate its own signal voltage. The frequency of this signal is determined by the inductive and capacitive properties of the circuit and may differ considerably from the frequency of the applied signal voltage. This condition is detrimental in an amplifier where only voltage or power gain of the incoming signal frequencies is desired.

Due to its 180° out-of-phase relationship, inverse feedback opposes and reduces the applied signal voltage, thereby lowering the effective overall gain of the amplifier stage. However, the loss of amplification can be readily overcome by using higher gain tubes or adding another amplifier stage. Despite the disadvantage of reduced amplifier gain, inverse feedback has the advantage of reducing amplitude distortion generated in that stage.

In some circuits, part of the distorted output is fed back to the input out-of-phase with the incoming signal. The distortions are combined with the applied input and amplified along with the desired signal. But, because of their out-of-phase relationship, they tend to cancel the distortion generated in the amplifier. As a result, distortion in the output is reduced considerably.

With no distortion in the amplifier, the feedback causes uniform reduction of all phases of the input signal. When distortion is present, the variations are fed back and cause unequal reductions of the input signal. Due to the out-of-phase relationship, a point of excess amplification on the output voltage waveform causes excessive reduction of the corresponding point of the input voltage waveform. With reduced input at this point, the output voltage will also be reduced, and the distortion is decreased.

Degenerative feedback also lessens the effects of frequency distortion. If certain frequencies are amplified more than others, the feedback voltage opposes and reduces them. Thus, those frequencies that obtain greater

amplification cause a higher feedback voltage, which reduces the effective signal and tends to make the amplification more uniform for all frequencies. As a result, there is an increase in the range of frequencies over which the amplifier operates satisfactorily. An inverse feedback circuit also reduces phase distortion.

In the case of each type of distortion, however, the reduction occurs only for that distortion which was produced within the feedback connections, and not for any which was introduced by preceding stages.

To summarize, the advantages of inverse feedback are reduction of harmonic distortion, improved frequency response and reduction of phase distortion.

Current Feedback

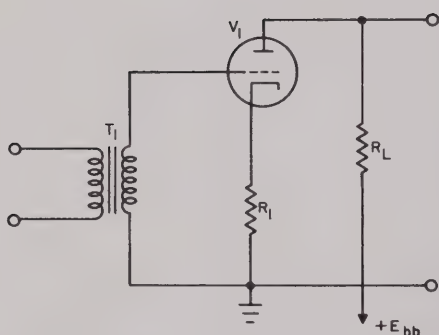


Figure 18

A simple circuit providing inverse feedback is shown in Figure 18. Resistor R_1 is the self-bias resistor. The bypass capacitor is omitted to obtain the desired feedback action. Without the capacitor, the voltage drop across R_1 varies with changes in plate current.

As explained previously, the voltage drop across the cathode resistor provides the negative grid bias in series with the input signal. Therefore, because the grid bias varies with the plate current, a portion of the output voltage is fed back to the grid, or input circuit, as a varying bias. With no signal on the grid, the plate current in resistor R_1 provides a voltage drop to bias the tube. When a positive signal pulse is applied, the grid becomes less negative, plate current increases, and the bias voltage developed across the cathode resistor increases. Since this increased bias tends to reduce the plate current, the current will not increase as much as when R_1 has a bypass capacitor across it.

When a negative input pulse is applied, the grid becomes more negative and the plate current is reduced. This reduction of current decreases the bias voltage. Therefore, the plate current is not reduced as much as when fixed bias is used.

This variable bias is proportional to the input signal, and since it opposes the signal, the bias variation is negative feedback voltage. In this circuit, the inverse feedback is developed by the changes in plate current, and therefore is known as **CURRENT FEEDBACK**.

Voltage Feedback

The circuit of Figure 19 utilizes a different method for obtaining negative feedback. Here, bypass capacitor C_2 is connected across cathode resistor R_3 to maintain a uniform bias voltage, regardless of plate current changes. A series network consisting of R_1 , C_1 and R_2 is connected from the plate to ground.

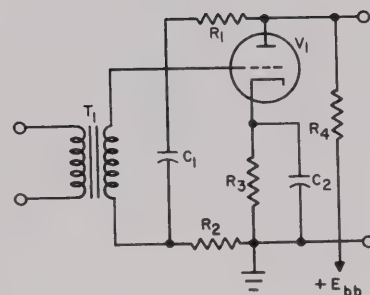


Figure
19

Capacitor C_1 blocks the dc component of the plate voltage, but for the ac component it acts as a high-pass filter with the output voltage across resistor R_2 . With a long time constant, most of the ac plate voltage appears across the resistors. The resistor values are proportioned so that the desired fraction of the total ac plate voltage is developed across R_2 .

Starting at the cathode of tube V_1 , the grid circuit extends to the grid, through the secondary of transformer T_1 , resistors R_2 and R_3 and back to the cathode. Thus, any voltage developed across R_2 is in series with the fixed bias across R_3 and the applied signal across the T_1 secondary. At any instant the total grid-cathode voltage is equal to the sum of these three voltages.

When a negative pulse of signal voltage occurs, the grid becomes more negative and the plate current is reduced. With less plate current there is a lower drop across load resistor R_4 and the plate voltage increases. Insofar as the $R_1C_1R_2$ network is concerned, this increase of plate voltage acts as a positive pulse; therefore, the resulting drop across R_2 opposes the applied signal voltage.

When a positive pulse of signal voltage occurs, the grid becomes less negative and the plate voltage decreases. This decrease of plate voltage is a negative pulse across the $R_1C_1R_2$ network. Again, the resulting voltage drop across R_2 opposes the applied signal voltage. In this circuit, the inverse feedback is developed by the changes in plate voltage, and is known as **VOLTAGE FEEDBACK**.

CATHODE FOLLOWERS

The load impedance of an amplifier is sometimes placed in the cathode circuit, usually between the cathode and ground. Such an arrangement is termed a grounded-plate amplifier, or more commonly, a **CATHODE FOLLOWER**.

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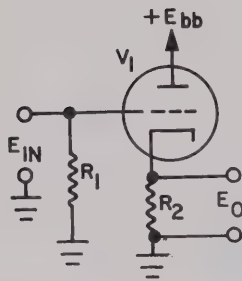


Figure
20

The circuit of a typical cathode follower is shown in Figure 20. As shown in the figure, the plate of V_1 connects directly to the plate supply. This places the plate at signal ground potential. The cathode load of V_1 is composed of R_2 . Cathode bias for V_1 is developed across R_2 . The output voltage is also developed across R_2 .

Assume that the positive alternation of an input signal is applied to the grid of V_1 . This causes an increase in V_1 plate current. The increased plate current causes an increase in the voltage drop across R_2 . From this action, we see that the input and output voltages are in phase.

Degenerative (negative) feedback is developed in the circuit due to the unby-passed condition of R_2 . This results in a decrease in amplifier gain. Because all of the output voltage is fed back to the input by R_2 , the voltage gain of a cathode follower is always less than 1.

The degenerative feedback introduced in the circuit of Figure 20 also increases the effective input impedance of the circuit. Therefore, the cathode follower has a high input impedance. The cathode load resistance is small, so that the cathode follower circuit has a low output impedance. The cathode follower may then be used as a matching device between a high-impedance input and a low-impedance output. Although it has no voltage gain, the cathode follower does develop a power gain and is sometimes used as a power amplifier.

DECOUPLING

In-phase, or regenerative, feedback of energy can cause unstable operation in a low-frequency amplifier. The regenerative feedback may cause the amplifier to generate an unwanted frequency which produces "singing" or "howling" if the unit drives a loudspeaker. Undesirable feedback of this type can be caused by magnetic fields coupling the input and output circuits of high-gain amplifiers, or by a coupling action in a power supply that feeds two or more stages.

To prevent magnetic coupling, many transformers and other inductive components are mounted in metal housings, or "cans," which act as shields. In other situations, connecting wires are enclosed in a metallic sleeve which serves as a shield to prevent unwanted inductive coupling.

Coupling can occur when the signal voltages cause sufficient changes of plate current in one stage to produce corresponding variations of the power

The following Practice Exercise questions cover the subjects which you have just studied. They are:

AMPLIFICATION REQUIREMENTS

HARMONICS

TYPES OF DISTORTION

INVERSE FEEDBACK

CURRENT FEEDBACK

VOLTAGE FEEDBACK

CATHODE FOLLOWERS

38. What is meant by the term "harmonic"?
39. What is the first harmonic of a 2000-Hz fundamental?
40. What is the fifth harmonic of a 50-Hz fundamental?
41. Push-pull operation eliminates _____ harmonics.
42. Describe what is meant by harmonic distortion, frequency distortion and phase distortion.
43. Intermodulation distortion is a form of _____ distortion.
44. One type of IM distortion generates _____ and _____ frequencies from the _____ frequencies.
45. What is the difference between regenerative and degenerative feedback?
46. What are some of the advantages and disadvantages of degenerative feedback?
47. What type of feedback is provided by an unbypassed cathode bias resistor?
48. What components in the circuit shown in Figure 19 provide the negative feedback?
49. In a cathode follower, the output signal is 180° out-of-phase with the input signal. True or False?

50. A cathode follower has a _____ input impedance and a _____ output impedance.
51. The voltage gain of a cathode follower is always less than 1. True or False?

supply voltage. Connected to the plate circuits of preceding stages, variations of the power supply voltages are amplified and cause even greater changes of plate current. Feedback of this type is regenerative, and therefore, it too can produce distortion and howling.

One method for preventing feedback through the power supply is called **DECOUPLING**. A typical arrangement of a low-pass RC network is shown in Figure 21. Generally, the time constant is long at the lowest signal frequency. Resistor R_2 is connected in series with the $+E_{bb}$ lead, and the capacitor, C_2 , is connected from point A to ground.

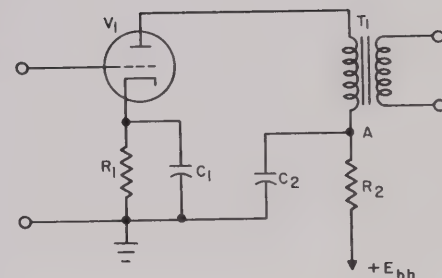


Figure 21

As the plate current decreases, the voltage drop across resistor R_2 also decreases. The potential at point A increases (with respect to ground) and charges capacitor C_2 to a higher voltage. The charging circuit is from capacitor C_2 through resistor R_2 and the power supply, from $+E_{bb}$ to ground and back to capacitor. Resistor R_2 then carries the sum of the plate current and the capacitor charging current.

As the plate current increases, the drop across resistor R_2 increases and lowers the potential at point A. Therefore, capacitor C_2 partly discharges. The plate current of tube V_1 divides at point A; part of it discharges capacitor C_2 and the remainder passes through resistor R_2 .

When the plate current decreases, capacitor C_2 charges, and the charging current tends to maintain the total current constant in R_2 . When the plate current increases, part of it is supplied by the discharge of C_2 , and again the change in the total R_2 current is reduced. Thus, the charge and discharge currents tend to maintain a constant current in R_2 , and therefore, a constant potential at point A. Because it removes the ac component of the plate current from resistor R_2 , C_2 is sometimes called a bypass capacitor. Do not confuse this term with the name given to C_1 , the cathode bypass capacitor. There are two current paths in the circuit of Figure 21. There is a dc path from ground through R_1 , tube V_1 , the primary of transformer T_1 , and R_2 to $+E_{bb}$. As the ac component is generated in the tube, its path can be traced from ground through C_1 , tube V_1 and the primary of T_1 , and through C_2 , back to ground.

TRANSFORMER PHASE INVERSION

The push-pull circuit of Figure 22 is often used to obtain increased power output from a stage, with less distortion than can be obtained from two tubes in parallel. Using the center tap on the secondary of input transformer T_1

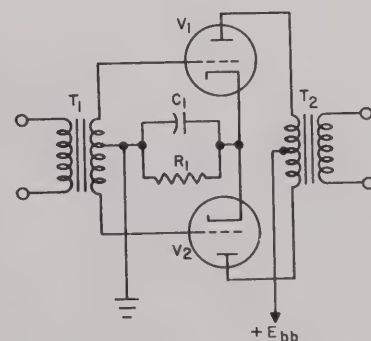


Figure 22

causes the signal voltage on the grid of tube V_1 to be 180° out-of-phase with the signal on the grid of V_2 . For this type of circuit, the generation of out-of-phase voltages is known as **PHASE INVERSION**.

Due to the economy in both weight and cost, it is often desirable to provide the necessary phase inversion by using resistors instead of transformers. There are several types of **PHASE INVERTER** circuits which produce the required conditions, but in general, they can be classed as (1) split plate load and (2) split grid load.

SPLIT PLATE LOAD PHASE INVERSION

A typical circuit of a **SPLIT PLATE LOAD PHASE INVERTER** is shown in Figure 23. The load resistance of input tube V_1 is divided into two parts: R_4 in the plate section, and R_2 in the cathode section. Resistor R_2 and capacitor C_2 provide the grid bias for tube V_1 .

The grid of tube V_2 is coupled to the plate of V_1 by capacitor C_3 , and the grid of tube V_3 is coupled to the cathode end of resistor R_3 by capacitor C_4 .

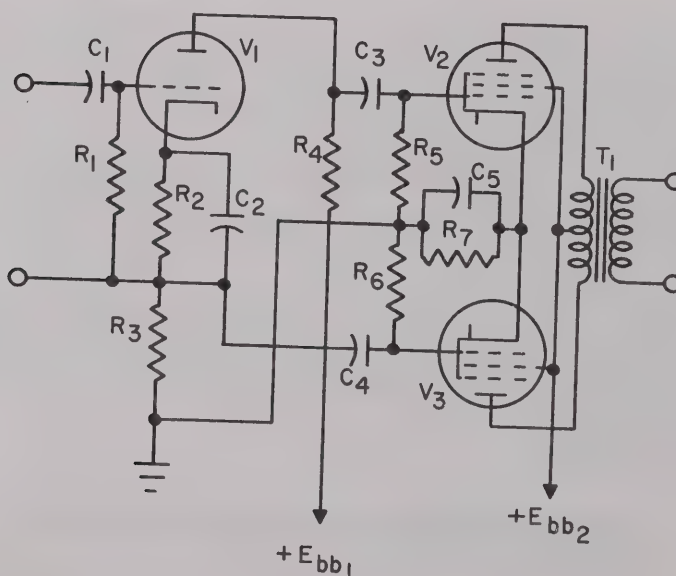


Figure 23

Since it is necessary to have equal magnitude voltages applied to the opposite control grids, R_4 is equal to R_3 , C_3 equals C_4 , and R_5 equals R_6 . Usually, any signal voltage across the bypass capacitor C_2 is not large enough to cause appreciable unbalance.

Tracing the plate circuit of the input tube, the path of the electrons is from ground through resistors R_3 and R_2 , through V_1 from cathode to plate, and back through resistor R_4 to $+E_{bb1}$. Since the grid circuit is connected to the junction between resistors R_2 and R_3 , the negative grid bias is developed by the R_2C_2 circuit.

Assuming the circuit is in operation, but with no signal input, there is a steady plate current which causes voltage drops across resistors R_3 , R_2 and R_4 so that capacitors C_2 , C_3 and C_4 are charged. Notice that capacitor C_3 connects from the plate of V_1 through R_5 to ground, while capacitor C_4 connects from the cathode end of R_3 through R_6 to ground.

When a signal voltage drives the grid of V_1 less negative, the V_1 plate current increases, causing the voltage drops across R_3 and R_4 to increase. This increased voltage drop causes the cathode end of R_3 to become more positive with respect to ground and increases the voltage across capacitor C_4 . To balance this increase, electrons flow from ground through R_6 to capacitor C_4 . This charging current develops a voltage drop in R_6 which drives the grid of V_3 less negative with respect to its cathode.

At the same time, the increased drop across R_4 reduces the V_1 plate voltage with respect to ground, and capacitor C_3 discharges sufficiently to balance the decrease. To obtain this balance, electrons forced from C_3 through R_5 develop a voltage drop across R_5 which drives the grid of V_2 more negative with respect to its cathode.

The signal voltages applied to the grids of tubes V_2 and V_3 are 180° out-of-phase, and therefore, their plate signal voltages are also 180° out-of-phase for proper push-pull operation. When using beam power tetrodes or pentodes, the screen grids are connected directly to $+E_{bb2}$ at the output transformer primary center tap, as shown in Figure 23.

SPLIT GRID LOAD PHASE INVERSION

Another phase inversion method, called the SPLIT GRID LOAD circuit, uses the opposite phase relations between the ac grid and plate voltages of

VACUUM TUBE LOW-FREQUENCY AMPLIFIERS

a tube. That is, when a signal voltage causes the grid to become more positive, the plate becomes less positive with respect to the common reference point or cathode. The signal voltages in the plate and grid circuits are 180° out-of-phase and, by amplifying the signal in one tube and picking off a part of the output voltage equal to that of the input, two signal voltages of the correct phase relationship and amplitude are obtained for push-pull operation.

A circuit using this method is shown in Figure 24. The output voltage of V_1 is applied to the grid of V_3 through coupling capacitor C_3 . A portion of the output voltage of V_1 is also applied to the grid of V_2 from the movable contact of potentiometer R_5 . The output voltage of V_2 is applied through coupling capacitor C_4 to the grid of V_4 .

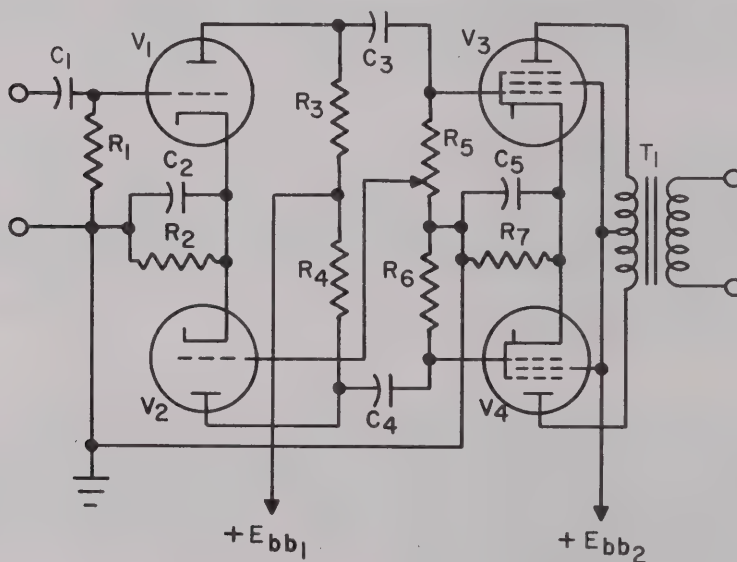


Figure 24

An increase of V_1 plate current reduces its plate voltage, causing coupling capacitor C_3 to discharge slightly. The resultant voltage drop across resistor R_5 drives the grid of V_3 more negative with respect to its cathode. Simultaneously, the voltage drop between the movable contact of R_5 and ground is applied to the grid of V_2 . V_2 is also driven more negative with respect to its cathode, causing a decrease of its plate current. This reduction in current increases the plate voltage of V_2 , forcing coupling capacitor C_4 to charge. The resultant voltage drop across resistor R_6 drives the grid of V_4 less negative with respect to its cathode.

The output voltage of V_2 is made equal to the output voltage of V_1 by adjusting the movable contact of R_5 . For example, if the voltage amplification of V_1 and V_2 is 10, the movable contact of R_5 is adjusted to supply one-tenth of the ac voltage across R_5 to the grid of V_2 . To balance the circuit, the value of R_3 is chosen so that it is equal to the value of R_4 , C_3 is equal to C_4 , and R_5 is equal to R_6 . Under these conditions, the voltage across R_6 is equal in magnitude to the voltage across R_5 . The signal voltage inputs to the push-pull grids of V_3 and V_4 are equal in magnitude and 180° out-of-phase.

AN AUDIO-FREQUENCY AMPLIFIER

Figure 25 is the complete schematic diagram of a simple amplifier, which incorporates several features explained in this lesson. Since no interstage transformers or chokes are indicated, resistance coupling is employed between the stages of the amplifier.

Briefly, the power supply is of the full-wave type, and rectification is accomplished by the diodes D_1 and D_2 . The rectified output is filtered by a modified form of RD network. In the plate supply circuit of tube V_{1A} , the 47K resistor and .1 μ F capacitor form a decoupling network.

Tube V_1 is a duotriode. To simplify the drawing, and as an aid in following the signal, the tube symbol is split into portions labeled V_{1A} and V_{1B} . In the diagram, these may be considered as two separate electron tubes, even though they are contained in the same envelope and have a single heater.

Following the signal from the MIKE input, audio-frequency voltages appear across the 5 M Ω grid load of V_{1A} . These signal voltages alter the bias on the tube, causing changes of plate current. The changes of current through the 220K plate load resistor provide the ac voltage or signal, which is coupled through a .01 μ F capacitor to the grid load of V_{1B} . The 1 M Ω potentiometer grid load is used as a volume control. Used as a variable voltage divider, the potentiometer applies a portion of the signal voltage appearing at the output of V_{1A} to the grid of V_{1B} . From the output of V_{1B} , the signal is coupled to the input circuit of the beam power output tube, V_2 . From the output of V_2 , the signal is then coupled by an output transformer to the loudspeaker, shown by the symbol at the right top portion of the figure.

Following the signal from the PHONO input, audio-frequency voltages are applied through the 100K resistor directly to the upper terminal of the volume

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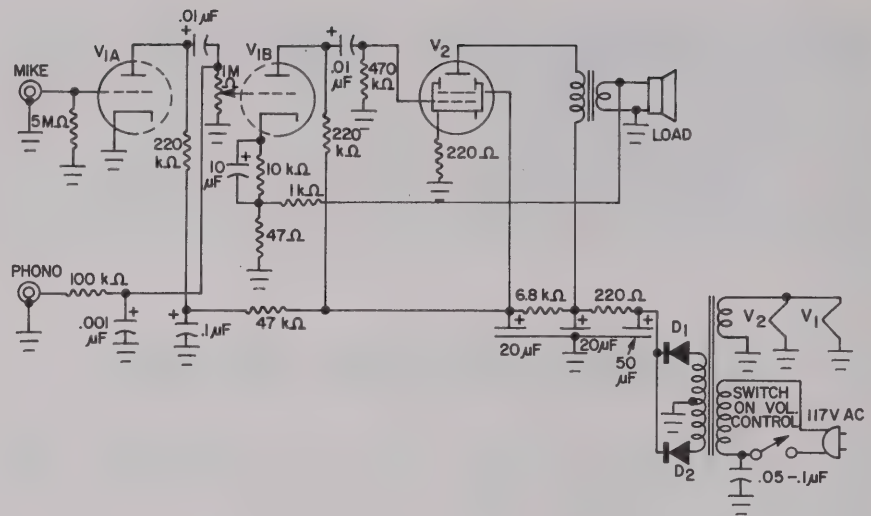


Figure 25

control. The reason for skipping a stage of amplification is because the output signal voltage of the phono pickup used is much greater than the output signal voltage of the particular microphone used with this amplifier. Usually, the output voltage of a microphone is much lower than the output voltage of a crystal or ceramic phono pickup. The 100K resistor and .001 μ F capacitor in the phono circuit form a low-pass filter to suppress some of the annoying high-frequency needle scratch caused by the pickup. From the volume control, the path of the phono signal is the same as that explained for the mike signal.

V_{1A} employs contact bias since the input resistance of 5 M Ω is large enough to cause a voltage drop of one or two volts. V_{1B} employs self-bias through the action of the parallel combination of the 10 μ F capacitor and the 10 k Ω resistor. The 47 Ω resistor in the cathode circuit is not effective in providing an appreciable bias, however. It is part of a voltage divider that consists of the 47 Ω resistor and the 1000 Ω resistor between the ungrounded output transformer secondary terminal and common ground. This divider provides voltage feedback.

In Figure 25, the source of the signal voltage for the speaker is the secondary of the output transformer. No blocking capacitor is required since this signal source does not carry any dc. Voltage appearing across the 47 Ω resistor provides about 5% feedback for improving the reproduction characteristics of the amplifier. Use of the unbypassed bias resistor in the cathode circuit of V₂ results in current feedback.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

DECOUPLING

TRANSFORMER PHASE INVERSION

SPLIT PLATE LOAD PHASE INVERSION

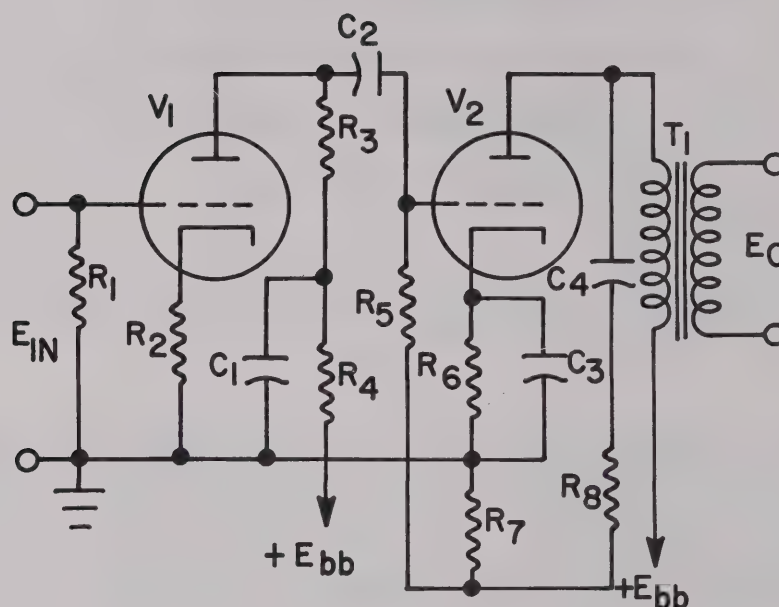
SPLIT GRID LOAD PHASE INVERSION

AN AUDIO-FREQUENCY AMPLIFIER

52. Metal shields are sometimes used to house inductors to prevent magnetic coupling. True or False?
53. It is desirable for changes of plate current in one amplifier stage to produce corresponding changes of power supply voltages. True or False?
54. What is meant by the term "decoupling"?
55. R_2 and C_2 , shown in Figure 21, serve as a _____-pass filter.
56. In Figure 22, the signal voltage applied to the grid of V_1 is 180° out-of-phase with the signal applied to the grid of V_2 because of (a) the C_1R_1 network, (b) the T_1 secondary center tap, (c) the T_2 primary center tap.
57. The most economical way to achieve phase inversion in an amplifier stage is to use a transformer. True or False?
58. How does a split plate load phase inverter develop the 180° out-of-phase output signals?
59. In the circuit shown in Figure 23, the cathode load resistor of V_1 is (a) R_2 , (b) R_3 , (c) R_4 , (d) R_1 .

60. In the circuit shown in Figure 24, is the signal at the grid of V_2 in phase or 180° out-of-phase with the signal at the plate of V_1 ?

61.



In the above circuit: (a) Give two functions of resistor R_2 . (b) Does resistor R_7 provide voltage or current feedback? (c) What is the function of capacitor C_3 ? (d) For what two purposes is capacitor C_2 used? (e) What is the C_1R_4 combination called? (f) What type of interstage coupling is used? (g) What type of bias is used for the V_2 stage?

If a suitable phase inverter and push-pull output stage had been used in this circuit, additional power output could be obtained. Thus, depending upon the service required, many circuit arrangements are possible to serve as low-frequency amplifiers. Yet, when the circuits are carefully analyzed, most of them fall within the various categories explained in this lesson.

SUMMARY

Signal frequencies between 0 Hz and 100,000 Hz are amplified by low-frequency amplifiers. Low-frequency amplifiers may be used as voltage or power amplifiers, depending upon the tubes and circuitry used.

Amplifiers are classed according to the length of time that plate current exists during the input cycle. In Class A operation, there is plate current for the full input cycle. In Class B operation, plate current exists for 180° of the input cycle. The efficiency of a Class B amplifier is greater than that of a Class A amplifier.

To increase the power output of an amplifier, its tubes may be operated in parallel or push-pull. Push-pull operation provides a greater power output with lower distortion than can be obtained with parallel operation. Phase inverters are used to supply the 180° out-of-phase signals required by a push-pull stage. Among the most common phase inverters are the split load and the center-tapped input transformer types.

Low-frequency amplifier stages may be either resistance, impedance or transformer coupled. Resistance coupling is the most common method since it provides relatively uniform frequency response with low cost, weight and size.

When part of the output signal of an amplifier is fed back to the input 180° out-of-phase with the input, the feedback is called negative, or degenerative. Its purpose is to reduce distortion produced by the stages of an amplifier within the feedback loop. The advantages of inverse feedback include: the reduction of harmonic distortion, an improved frequency response and a reduction of phase distortion.

IMPORTANT DEFINITIONS

AMPLITUDE DISTORTION — A form of distortion in low-frequency amplifiers, in which harmonics of the input signal are generated in the amplifier and appear with the signal at the output. Also called **HARMONIC DISTORTION**.

CASCADE STAGES — The connection of two or more amplifiers with the output of one stage fed to the input of the next.

CATHODE BIAS — The use of the voltage drop across a resistor in the cathode circuit as a source of grid bias. Also referred to as self-bias.

CATHODE BYPASS CAPACITOR — A bypass capacitor placed across the cathode bias resistor to keep the bias constant.

CATHODE FOLLOWER — A common plate amplifier in which the load resistor is located in the cathode circuit.

CLASS A AMPLIFIER — A circuit in which the tube is biased so that it conducts throughout the full 360° of the grid voltage cycle.

CLASS AB AMPLIFIER — A circuit in which the tube is biased so that it conducts for more than half, but less than the entire grid voltage cycle.

CLASS B AMPLIFIER — A circuit in which the tube is biased practically to cutoff, and therefore conducts during approximately 180° of the grid voltage cycle.

CLASS C AMPLIFIER — A circuit in which the tube is biased beyond cutoff, and therefore conducts for less than 180° of each grid voltage cycle.

CONTACT BIAS — The use of a very high value resistance in the grid circuit of a tube to develop a bias voltage which results from the minute grid current that flows.

CURRENT FEEDBACK — Feedback caused by changes of plate current.

DECOUPLING — The reduction of the transfer of energy from one circuit to another through the power supply, usually by means of low-pass filters.

DEGENERATIVE FEEDBACK — The transfer of energy from one point back to a previous one in a circuit so that the signals are out-of-phase with each other. Also known as inverse or negative feedback.

IMPORTANT DEFINITIONS (Continued)

DISTORTION — In electronics, any unwanted change in the output waveform as compared to the input waveform.

FEEDBACK — The transfer of energy from one point in an electric circuit to a preceding point.

FIXED BIAS — A grid bias arrangement where a fixed value of voltage is derived from a power supply or battery.

FREQUENCY DISTORTION — The distortion introduced into a signal when some frequency components are amplified more than others.

FREQUENCY RESPONSE — The range of frequencies that receives equal amplification by a circuit.

FUNDAMENTAL — The lowest frequency of a complex sound or signal. It is usually the largest in amplitude.

GRID-LEAK BIAS — A bias arrangement where the input signal drives the grid positive, charging a capacitor. The discharge of the capacitor through the grid circuit resistance develops the bias voltage.

HARMONICS — Frequencies which are whole number multiples of a fundamental frequency.

HARMONIC DISTORTION — See AMPLITUDE DISTORTION.

IMPEDANCE-COUPLED — An interstage coupling arrangement resembling RC coupling in which a choke coil is used instead of the load resistance.

INTERMODULATION DISTORTION — A form of amplitude distortion that may occur when two or more input frequencies are simultaneously amplified.

INVERSE FEEDBACK — See DEGENERATIVE FEEDBACK.

NEGATIVE-LEG BIAS — A bias arrangement where a resistance is placed in the negative lead of the power supply to develop the bias voltage.

PARALLEL OPERATION — Two or more tubes connected in a circuit so that the grids, the plate and the cathodes are respectively connected to the same circuit elements.

PHASE DISTORTION — The distortion introduced into a signal when the relative phase between components of different frequencies is changed.

IMPORTANT DEFINITIONS (Continued)

PHASE INVERSION — The method whereby two equal signals which are 180° out-of-phase with each other are obtained from the same signal.

PHASE INVERTER — A circuit designed to obtain phase inversion. Also called a phase splitter.

POWER AMPLIFIER — An amplifier primarily designed to increase the power of the signal applied to its inputs.

PROJECTED CUTOFF BIAS — The bias of the Class B amplifier determined by projecting the linear portion of the tube I_b - E_c curve to where the composite curve crosses the zero plate current line.

PUSH-PULL AMPLIFIER — A two-tube amplifier circuit consisting of one tube connected so that it is electrically 180° out-of-phase with the other tube. This arrangement is used to improve the linearity of the combined characteristic I_b - E_c curve. Properly operated, the push-pull amplifier provides increased power output with reduced distortion.

REGENERATIVE FEEDBACK — The transfer of energy from a point in a circuit to a preceding point so that the signals are in phase.

RESISTANCE-CAPACITANCE (RC) COUPLING — An interstage coupling arrangement employing resistors and capacitors. Also called RESISTANCE COUPLING.

RESISTANCE COUPLING — See RESISTANCE-CAPACITANCE (RC) COUPLING.

SELF-BIAS — See CATHODE BIAS.

SPLIT PLATE LOAD PHASE INVERTER — An amplifier stage with load resistors in the plate and cathode circuits.

TRANSFORMER-COUPLED — An interstage coupling arrangement employing a transformer.

VOLTAGE AMPLIFIER — An amplifier designed to increase the voltage of a signal.

VOLTAGE FEEDBACK — Feedback caused by changes of plate voltage.

VOLTAGE GAIN (A_v) — A ratio between the output and input voltages of an amplifier.

ESSENTIAL SYMBOLS AND EQUATIONS

A_v	Voltage gain
E_{IN}	Input voltage (volts)
E_o	Output voltage (volts)
I_1	Input current (amperes)
I_2	Output current (amperes)
P_1	Input power (watts)
P_2	Output power (watts)
R_L	Plate load resistance (ohms)
r_p	Internal plate resistance (ohms)
μ	Amplification factor

$$A_v = \frac{E_o}{E_{IN}} \quad (1)$$

$$A_v = \frac{\mu \times R_L}{R_L + r_p} \quad (2)$$

PRACTICE EXERCISE SOLUTIONS

1. The voltage gain (A_v) of an amplifier is equal to $\frac{E_o}{E_{IN}}$.

2. The voltage gain is 20:

$$A_v = \frac{E_o}{E_{IN}} = \frac{30V}{1.5V} = 20.$$

3. The voltage gain is 74:

$$\begin{aligned} A_v &= \frac{\mu \times R_L}{R_L + r_p} = \frac{1 \times 10^2 \times 1 \times 10^5}{10 \times 10^4 + 3.5 \times 10^4} = \frac{1 \times 10^7}{13.5 \times 10^4} \\ &= 7.4 \times 10^1 \\ &= 74. \end{aligned}$$

4. A voltage amplifier is used to increase only the voltage level of a signal. A power amplifier, on the other hand, increases the power (voltage $\times$ current) level of a signal.
5. The difference between the amplifier classes is the length of time plate current flows during the input signal cycle. In a Class A amplifier, plate current flows for the full input cycle (360°). In the Class B amplifier, plate current flows for one half the input cycle (180°). In a Class C amplifier, plate current flows for less than one half the input cycle.
6. The input signal level and value of bias voltage determines if operation is confined to the linear portion of the characteristic curves.
7. The negative alternation will be distorted, since the negative alternation of the input signal will drive the tube into cutoff.
8. The efficiency of an amplifier is the ratio of signal power output (product of output signal voltage and current) to the dc input power from the power supply (product of plate current and plate voltage).
9. The efficiency of a Class A amplifier is approximately 25% for triodes and 30% for tetrodes and pentodes.
10. The bias for Class B operation is set so that the operating point is at cutoff.
11. Yes — A Class B amplifier can handle a larger signal than a similar Class A amplifier.
12. The efficiency of a Class B amplifier is between 50 and 65%.

PRACTICE EXERCISE SOLUTIONS (Continued)

13. A Class AB amplifier is an amplifier in which plate current exists for more than 180° but less than 360° of the input signal cycle.
14. Yes — The subscript 2 indicates that grid current is being drawn.
15. fixed
16. No—Fixed bias is generally used in Class B and Class C amplifiers where operation is at or beyond plate current cutoff.
17. Plate current flowing through the cathode resistor develops a voltage drop which makes the grid negative with respect to the cathode.
18. C_1 keeps the cathode bias constant by serving as a cathode bypass capacitor.
19. long — With a long time constant, the cathode voltage will remain constant under signal conditions.
20. The bypass capacitor reactance should be $1/10$ of 250 ohms, or 25 ohms.
21. The bias is developed by the discharge of C_1 through R_1 . C_1 is charged when the input signal drives the grid of V_1 positive, developing grid current.
22. True — A contact potential bias arrangement requires a grid resistance on the order of $10\text{ M}\Omega$.
23. The value of the cathode bias resistor is equal to:

$$\begin{aligned}
 R_2 &= \frac{E_c}{I_b + I_{c2}} = \frac{2}{10 \times 10^{-3} + 2 \times 10^{-3}} = \frac{2}{12 \times 10^{-3}} \\
 &= .167 \times 10^3 \\
 &= 167 \text{ ohms.}
 \end{aligned}$$

24. The reactance of C_1 should be $1/10$ the value of R_2 :

$$\begin{aligned}
 C &= \frac{1}{2\pi f X_C} = \frac{1}{6.28 \times 1 \times 10^2 \times 1.67 \times 10^1} = \frac{1}{10.5 \times 10^3} \\
 &= .095 \times 10^{-3} \\
 &= 95 \text{ } \mu\text{F.}
 \end{aligned}$$

PRACTICE EXERCISE SOLUTIONS (Continued)

25. The coupling capacitor blocks the dc voltage from the plate of the previous stage and transfers the amplified ac signal to the grid of the next stage.
26. As the plate voltage increases and decreases, the coupling capacitor charges and discharges through the grid load resistor of the next stage. The voltage developed across the grid load resistor serves as the input signal to the next stage.
27. The low-frequency response is determined by the values of C_2 and R_3 . The high-frequency response is determined by the value of the shunt capacitance, C_x .
28. long — Since the coupling circuit is basically a high-pass filter, the circuit time constant must be long to pass the low frequencies.
29. An impedance-coupled amplifier employs an inductance for the plate load whereas an RC coupled amplifier employs a resistor for the plate load.
30. Generally, the maximum turns ratio is 3:1 step-up. Distributed capacitance and losses limit the turns ratio.
31. B — The grid current drawn by a Class B amplifier requires a low driving impedance which can easily be provided by a step-down transformer.
32. The power output from a parallel amplifier is twice that of a comparable single stage.
33. A push-pull amplifier requires 180° out-of-phase grid signals.
34. True — Under no-signal conditions the magnetic flux developed in each half cancels.
35. Push-pull operation reduces distortion due to the canceling effect.
36. Yes — A push-pull amplifier develops a larger peak-to-peak output than a parallel amplifier.
37. No — They are operated slightly above cutoff to prevent distortion of the output signal.
38. A harmonic is a frequency which is a whole number multiple of the fundamental frequency.

PRACTICE EXERCISE SOLUTIONS (Continued)

- 39. 2000 Hz. — The first harmonic is the fundamental frequency.
- 40. 250 Hz. — The first harmonic is 50 Hz; the second is 100 Hz; the third is 150 Hz; the fourth is 200 Hz; and the fifth harmonic is 250 Hz.
- 41. even — The combining action of push-pull operation cancels the even harmonics.
- 42. Harmonic distortion refers to the generation of harmonics from a fundamental signal as it is amplified. Frequency distortion occurs when some harmonics are amplified more than the other harmonics. Phase distortion occurs when some harmonics have different phase shifts than other harmonics.
- 43. amplitude
- 44. sum; difference; input
- 45. With regenerative feedback, part of the output signal is applied back to the input so that it aids the input signal. Regenerative feedback results in an increase of the output signal amplitude. Conversely, with degenerative feedback, part of the output signal is applied back to the input so that it opposes the input signal. Degenerative feedback results in a decrease of the output signal amplitude.
- 46. Degenerative feedback increases the frequency response and reduces distortion. However, degenerative feedback reduces the stage gain.
- 47. An unbypassed cathode resistor provides negative current feedback.
- 48. R_1 , R_2 and C_1 provide the negative voltage feedback for the stage.
- 49. False — The input and output signals are in phase in a cathode follower.
- 50. high; low — A cathode follower can serve as an impedance matcher to match a high impedance to a low impedance.
- 51. True — Due to the large amount of inverse feedback, the voltage gain of a cathode follower is always slightly less than one.
- 52. True
- 53. False — Variations of power supply voltages are amplified by the following stages, causing even greater variations of plate current. This results in distortion of the amplified signal frequencies.

PRACTICE EXERCISE SOLUTIONS (Continued)

54. Decoupling refers to the use of filter networks to prevent feedback through the power supply.
55. low — The R_1C_1 decoupling network serves as a low-pass filter. The network will pass the power supply voltage and attenuate the signal frequencies.
56. (b) the T_1 secondary center tap.
57. False — Due to the economy in both weight and cost, it is often desirable to provide the necessary phase inversion by using resistors and capacitors instead of transformers.
58. A split plate load phase inverter employs a load resistor in both the cathode and plate circuits. The signals developed in the cathode and plate circuits are 180° out-of-phase with each other.
59. (b) R_3 . — R_2 is used to develop the cathode bias. R_4 is the plate load resistor. R_1 is the grid load resistor.
60. The signal at the grid of V_2 is in phase with the signal at the plate of V_1 , since a portion of the signal at the plate of V_1 is used as the input signal applied to the grid of V_2 .
61. (a) Resistor R_2 develops the grid bias voltage and provides negative current feedback. (b) Resistor R_7 provides voltage feedback. (c) Capacitor C_3 maintains a steady grid bias voltage. (d) Capacitor C_2 couples the signal from V_1 to V_2 and blocks dc from the grid of V_2 . (e) The C_1R_4 combination is called a decoupling network. (f) Resistance coupling is used for interstage coupling. (g) Cathode (self-) bias is employed in the V_2 stage.

NOTICE: To keep our lessons up-to-date, we add material to the texts from time to time, and make occasional changes in the examination questions. Therefore, when checking your answers with this check sheet, look at the code LETTER (A, B, C, etc.) on your examination sheet to determine which of the following groups of answers apply to the lesson which you have.

1076B

1. B - THE DURATION OF PLATE CURRENT IN A CLASS A AMPLIFIER IS -- 360°.
A Class A amplifier is biased so that plate current flows for 360° of the input signal cycle.

2. C - SUPPOSE THAT IN THE CIRCUIT OF FIGURE 6, R_L HAS A VALUE OF 47 kΩ AND THE VOLTAGE DROP ACROSS R_L IS 100 VOLTS. WHAT IS THE GRID BIAS VOLTAGE IF R_1 HAS A VALUE OF 1 kΩ? -- 2.13 VOLTS.

To determine the grid bias, the plate current is first determined:

$$I_b = \frac{E_{R_L}}{R_L} = \frac{100}{47 \times 10^{-3}} = 2.13 \times 10^{-3} = 2.13 \text{ mA}$$

The grid bias voltage is therefore:

$$E_c = I_b \times R_1 = 2.13 \times 10^{-3} \times 1 \times 10^3 = 2.13 \text{ volts.}$$

3. D - COMPARED TO CLASS A, CLASS B OPERATION OF A TUBE -- PROVIDES AN INCREASE IN EFFICIENCY.

Class A operation provides an efficiency of about 25% to 30%. Class B operation provides an efficiency of about 50% to 65%.

4. A - THE PURPOSE OF C_1 IN FIGURE 6 IS TO -- PREVENT DEGENERATIVE FEEDBACK.

When the cathode bias resistor is unbypassed, negative or degenerative current feedback is introduced. This reduces gain but lowers distortion and improves frequency response.

5. B - FOR GOOD LOW-FREQUENCY RESPONSE IN THE CIRCUIT OF FIGURE 10, -- THE C_2R_3 TIME CONSTANT SHOULD BE LONG.

C_2 and R_3 form a high pass filter. To provide minimum attenuation at low frequencies, the time constant should be long.

6. B - IN A PUSH-PULL AMPLIFIER -- EVEN HARMONIC DISTORTION IS CANCELLED.

The combining action of push-pull operation cancels even harmonic distortion. This action also cancels the steady state magnetic flux in the output transformer.

7. C - THE PHASE RELATIONSHIP BETWEEN THE INPUT SIGNAL AND OUTPUT SIGNAL IN THE CIRCUIT OF FIGURE 20 IS -- 0°.

In a cathode follower circuit, the input and output signals are in phase.

8. D - THE CALCULATED VOLTAGE GAIN OF A STAGE LIKE THAT OF FIGURE 1 WHEN $R_L = 10,000$ OHMS, $r_p = 20,000$ OHMS AND $\mu = 30$ IS -- 10.

The voltage gain of a triode amplifier is equal to

$$A_v = \frac{\mu R_L}{R_L + r_p} = \frac{30 \times 1 \times 10^4}{1 \times 10^4 + 2 \times 10^4} = \frac{30 \times 10^4}{3 \times 10^4} = 10.$$

9. D - THE CIRCUIT OF FIGURE 23 EMPLOYS A -- SPLIT LOAD PHASE INVERTER.

The V_1 stage serves as a split load phase inverter to supply the required 180° out of phase signals to the push-pull stage.

10. C - DEGENERATIVE FEEDBACK -- REDUCES GAIN.

Although degenerative feedback reduces gain, it also reduces distortion and improves frequency response.

1076A

All explanations are the same as for 1076B except those given below.

5. B - FOR GOOD LOW FREQUENCY RESPONSE IN THE CIRCUIT OF FIGURE 11, -- THE C_2R_3 TIME CONSTANT SHOULD BE LONG.

C_2 and R_3 form a high pass filter. To provide minimum attenuation at low frequencies, the time constant should be long.

1076A & B

EXPERIMENT 6

CLASS A AND B VACUUM TUBE AMPLIFIERS

PARTS NEEDED

- | | |
|--|---|
| 1 - Complete Design Console | 1 - 1 M Ω Potentiometer with Bracket and Leads |
| 1 - Multimeter with Test Leads and Spring Adapters | 1 - 1 k Ω , 1/2 W, 20% Resistor |
| 1 - 9-Pin Tube Socket with Leads | 1 - 100 k Ω , 1/2 W, 20% Resistor |
| 11 - Modular Connectors | 2 - Tri-mounts |
| 1 - 12AU7 Tube | - No. 22 Solid Hookup Wire |

OBJECTIVE

The class of operation in a vacuum tube amplifier circuit is dependent upon the value of grid bias. In this experiment you will observe the basic characteristics of Class A and Class B common-cathode amplifier circuits. The variable low voltage power supply on the design console will be used to vary the bias and thus set the class of operation.

PART 1

PROCEDURE

CLASS A AMPLIFIERS

1. Set up the circuit of Figure 6-1 following the layout of Figure 6-2. R_1 controls the input signal level. Set the shaft on R_1 fully counterclockwise and set the ADJUST FREQ. control to mid-range, 5. Rotate the ADJUST VOLTAGE control fully counterclockwise and turn on the design console. The regulated low voltage power supply should be set to 30 volts. Allow a 5 minute warm up.

2. To set up the amplifier circuit for Class A operation, measure the V_1 plate-to-ground dc voltage; and set the ADJUST VOLTAGE control for a plate voltage of 90 volts. This sets the bias so that the voltage at the plate in reference to ground is approximately one-half of the supply voltage.

Measure the cathode-to-ground voltage (bias), and record it below.
Class A Grid Bias = _____ volts dc

The Class A bias voltage should be somewhere in the range of 5 volts.

3. Using the output function of your multimeter, measure the output ac voltage (plate-to-ground), E_O , and adjust R_1 clockwise until you obtain an output of 50 volts ac. Now measure the input signal (grid-to-ground), E_{IN} , and record

Class A and B Vacuum Tube Amplifiers

it below. Use the same range on the meter as for the output voltage to prevent meter loading errors. Record the input voltage below.

Input Signal, E_{IN} , = _____ volts ac

4. Using the measured input signal from Step 3 and the 50 volt output signal amplitude, calculate the voltage gain and record it.

$$\text{Voltage Gain, } A_V = \frac{E_O}{E_{IN}} = \frac{50V}{E_{IN}} = \underline{\hspace{2cm}} = \underline{\hspace{2cm}}$$

Since the μ of the tube has an average value of 20, your voltage gain should be less than 20. However, a given tube may have a higher gain and thus some variation in gain is possible.

5. In a Class A amplifier, the dc plate voltage remains constant with or without a signal. The dc plate voltage was set earlier to 90 volts. Remeasure the dc plate voltage and record.

DC Plate Voltage with Signal = _____ volts dc

Your measured plate voltage should again be close to 90 volts, indicating that the operating point does not shift when a signal is applied.

PART 2

PROCEDURE

CLASS B AMPLIFIERS

1. To set up the amplifier circuit for Class B operation, first reset R_1 fully counterclockwise. While measuring the V_1 dc plate voltage, set the ADJUST VOLTAGE control for a dc plate voltage of 150 volts. Although this is not quite at cutoff, it is close enough for our experiment. Measure and record the bias voltage (cathode-to-ground voltage).

Class B Grid Bias = _____ volts dc

A rough approximation of the required cutoff bias voltage for a triode is found by dividing the plate voltage by the μ . Since the plate voltage is approximately 180 volts and the μ is 20, the approximate cutoff bias voltage is $180 \div 20$ or 9 volts. Your measured cutoff bias voltage should be about 9 or 10 volts.

2. To check the voltage gain of your Class B amplifier, set R_1 fully clockwise. This supplies maximum input to the circuit and is necessary to overcome the high bias voltage. Measure the input (grid-to-ground), E_{IN} , and output (plate-to-ground), E_O , ac voltages. Be sure to use the output function of the multimeter to measure the ac voltages.

Class A and B Vacuum Tube Amplifiers

Input Voltage, E_{IN} = _____ volts ac

Output Voltage, E_O = _____ volts ac

3. Using the values from Step 3, calculate the voltage gain of the Class B circuit.

$$\text{Voltage Gain, } A_V = \frac{E_O}{E_{IN}} = \frac{\quad}{\quad} = \frac{\quad}{\quad}$$

Your calculated gain should be less than that for the Class A circuit, approximately one-half of the Class A gain calculated in Step 4 of Part 1. Remember, with Class B operation, only one alteration of the input signal is amplified for an output, thus the gain appears to be about one-half of the Class A gain.

4. A characteristic of Class B operation is a change in the dc plate voltage under operating conditions. With R_1 still set fully clockwise, measure the V_1 dc plate voltage and record it below.

DC Plate Voltage with Signal = _____ volts dc

Your measured dc plate voltage under signal conditions should be less than what it was for no signal. This indicates a shift in the operating point under signal conditions.

CONCLUSION

A Class A common-cathode amplifier has a high voltage gain, and the dc operating conditions do not vary with the signal. With Class B operation, the dc operating conditions shift down from cutoff when a signal is applied. In addition, the voltage gain appears lower since only one half the input signal is amplified. The cutoff bias for Class B operation of a triode is approximately equal to the plate voltage divided by the μ of the tube.

NOTES

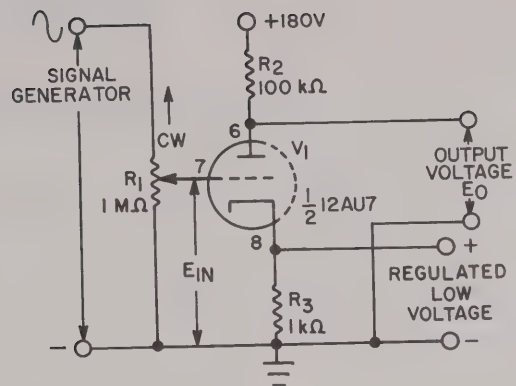


FIGURE 6-1

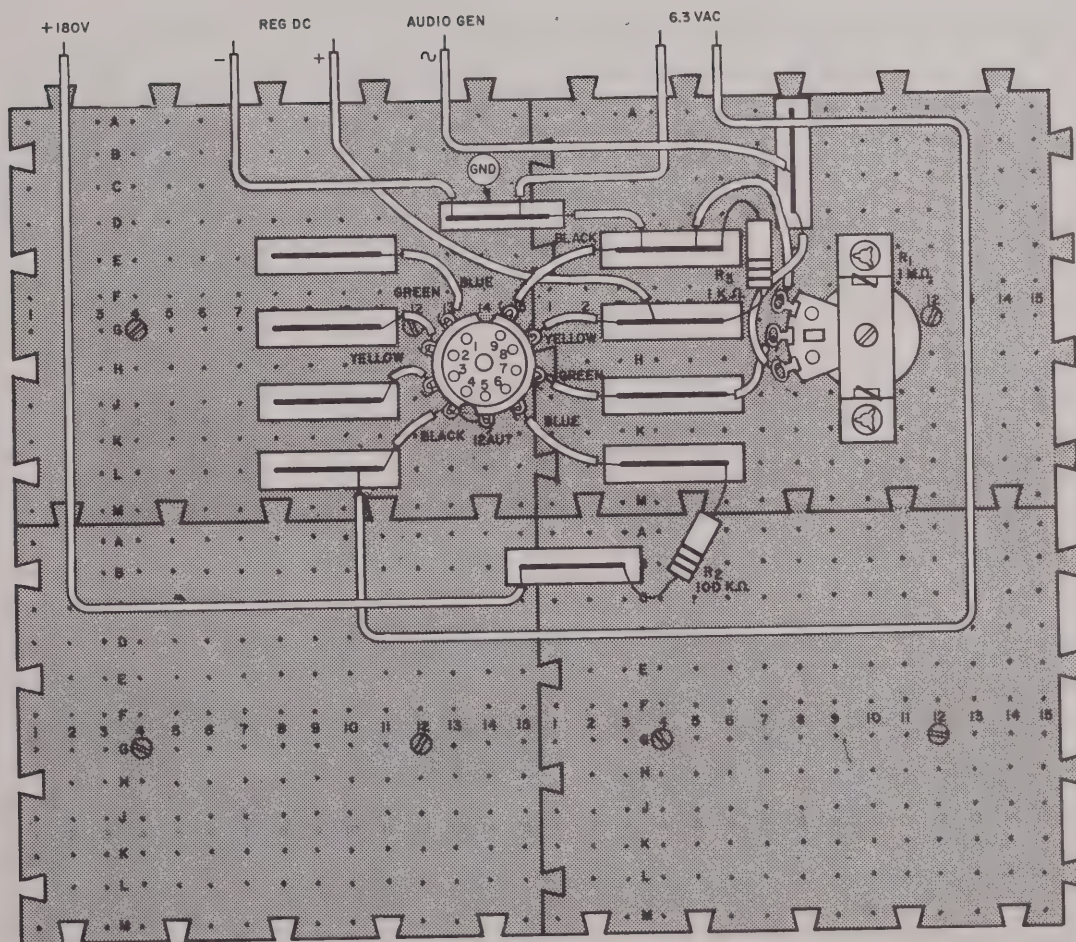


FIGURE 6-2

NOTES

1. B - WHEN AN INPUT SIGNAL IS APPLIED TO A CLASS A AMPLIFIER, THE DC PLATE VOLTAGE -- REMAINS THE SAME.
In a Class A amplifier, the operating point does not change when a signal is applied, and thus the dc plate voltage remains constant.

2. A - SUPPOSE THAT A CLASS A AMPLIFIER IS OPERATED WITH A PLATE SUPPLY VOLTAGE OF 150 VOLTS. A TYPICAL DC PLATE VOLTAGE FOR CLASS A OPERATION IS -- 75 VOLTS.
Typically, for Class A operation the dc plate voltage will be one-half of the dc supply voltage.

3. D - WITH RESPECT TO VOLTAGE GAIN, -- A CLASS A AMPLIFIER APPEARS TO HAVE A HIGHER VOLTAGE GAIN THAN A CLASS B AMPLIFIER.
A Class A amplifier has a higher voltage gain than a Class B circuit since the Class A stage amplifies the full 360° swing of the input signal.

4. B - IF A TRIODE HAS A μ OF 50 AND A PLATE VOLTAGE OF 250 VOLTS, WHAT IS THE APPROXIMATE CUTOFF BIAS? -- 5 VOLTS.
The approximate cutoff bias for a triode is the dc plate supply voltage divided by the μ of the tube:

$$\text{CUTOFF BIAS} = \frac{250\text{V}}{50} = 5\text{V.}$$

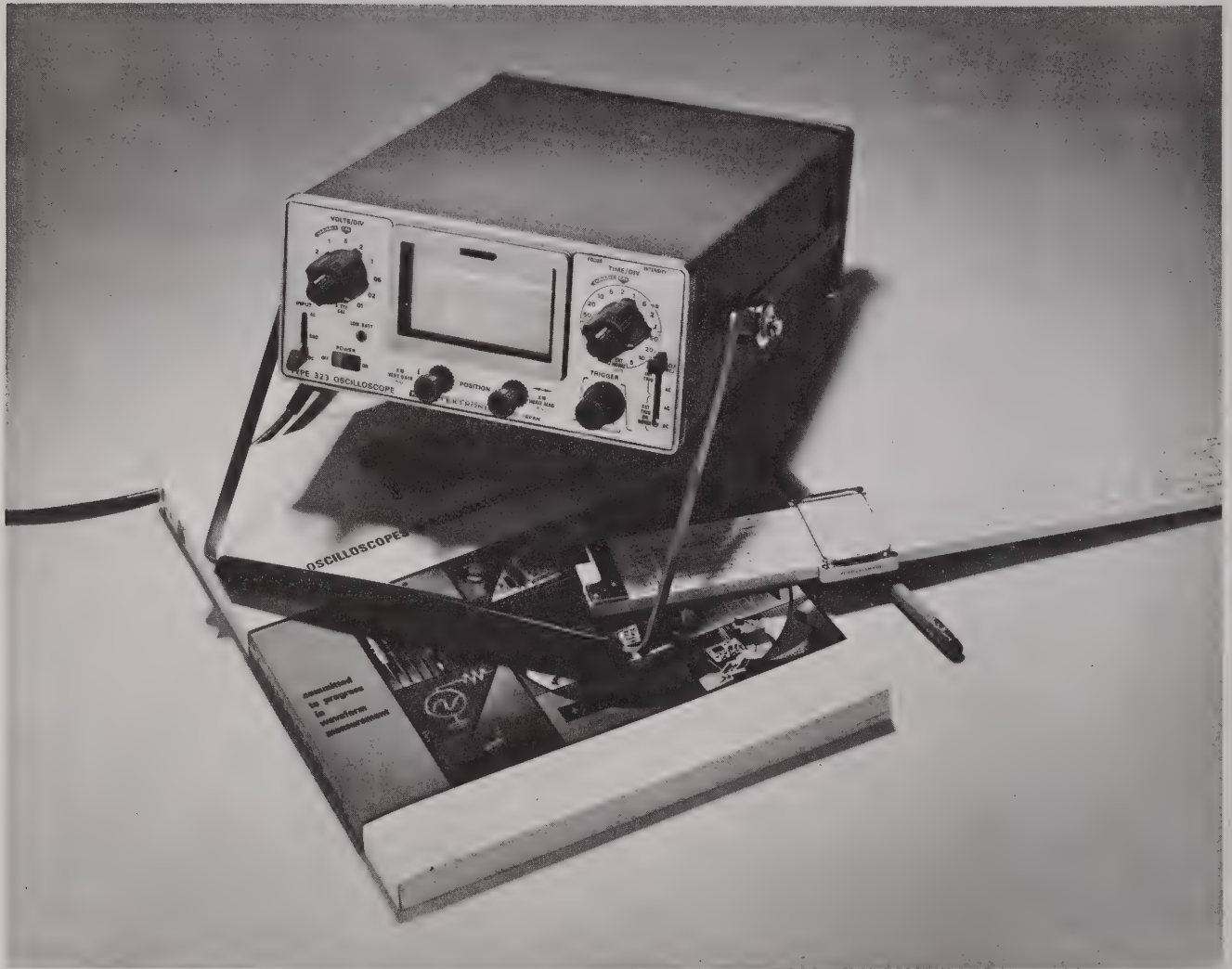
5. C - WHEN AN INPUT SIGNAL IS APPLIED TO A CLASS B AMPLIFIER, THE DC PLATE VOLTAGE -- DECREASES.
Under no signal conditions, the tube is just at cutoff in a Class B amplifier. When a signal is applied, the average dc plate voltage decreases.

TRANSISTOR LOW-FREQUENCY AMPLIFIERS

1079

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Transistors make possible portable test equipment, such as this solid state oscilloscope. This instrument operates on ac or dc line voltages or from rechargeable batteries. The oscilloscope can display the waveforms of low-frequency amplifiers and does have one tube — the cathode-ray tube.

Courtesy Tektronix, Inc.

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*Every day gives you another chance.
—Selected*

TRANSISTOR LOW-FREQUENCY AMPLIFIERS

Since its development in 1948, the transistor has grown to be a giant in the electronics industry. New and better transistors are being manufactured every day. Power ratings are increasing. New transistors are capable of amplifying higher frequency signals at higher power levels. Transistors are finding wide use as amplifiers. This lesson discusses the various types of transistor amplifiers and related circuits.

VOLTAGE AND POWER AMPLIFIERS

Amplifiers are classed according to the kind of output they supply to their loads. A load that requires a large signal voltage but little current is supplied by an amplifier that increases a small input voltage to a large output voltage. This type of amplifier is called a **VOLTAGE AMPLIFIER**. One type of voltage-operated load is the cathode-ray tube used in an oscilloscope.

Conversely, an amplifier that supplies a large signal current to a current-operated load is sometimes called a **CURRENT AMPLIFIER**. Although this type of amplifier is common, the term "current amplifier" is seldom used for this purpose. Two examples of loads that need sizable signal currents are relays and speakers. Usually, these loads are thought of in terms of both the signal current and voltage signal that they need. Since the product of voltage and current is power, the amplifiers which drive these loads are more often called **POWER AMPLIFIERS**. In such amplifiers, the power delivered to the load can be from a fraction of a watt to well over 100 watts.

The term **GAIN** is used to express the ratio of the input signal voltage, current or power to the output signal voltage, current or power of an amplifier. In the form of equations, the voltage, current and power gains can be expressed as follows:

$$A_V = \frac{V_{OUT}}{V_{IN}} \quad (1)$$

where: A_V = voltage gain,

V_{OUT} = output voltage, and

V_{IN} = input voltage.

$$A_I = \frac{I_{OUT}}{I_{IN}} \quad (2)$$

where: A_I = current gain,

I_{OUT} = output current, and

I_{IN} = input current.

$$A_P = \frac{P_{OUT}}{P_{IN}} = A_V \times A_I \quad (3)$$

where: A_P = power gain,

P_{OUT} = output power, and

P_{IN} = input power.

TRANSISTOR AMPLIFIER TYPES

A transistor may be used in three types of amplifier circuit configurations. Each type has particular characteristics which make it suitable for specific applications.

Probably the most often used transistor amplifier configuration is the **COMMON-EMITTER (CE) AMPLIFIER**. This type of amplifier is shown in Figure 1. An NPN transistor is shown in Figure 1A while Figure 1B shows a PNP circuit. The only differences between the two circuits are the direction of current and the polarities of the supply voltages. In both circuits, the emitter junctions must be forward biased, and the collector junctions must be reverse biased. V_{BB} provides the forward bias for the emitter junction and V_{CC} provides the reverse bias for the collector junction.

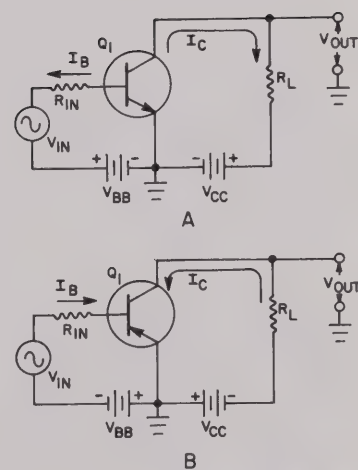


Figure 1

IN AN NPN TRANSISTOR AMPLIFIER CIRCUIT, THE BASE AND COLLECTOR ARE BOTH MORE POSITIVE THAN THE EMITTER. IN A PNP TRANSISTOR AMPLIFIER CIRCUIT, THE BASE AND COLLECTOR ARE BOTH MORE NEGATIVE THAN THE EMITTER.

TRANSISTOR LOW-FREQUENCY AMPLIFIERS

In a common-emitter amplifier, the input signal causes variations of base current. In turn, the base current causes collector current to vary. The collector current (I_C) is approximately equal to the base current (I_B) times the current gain h_{fe} (β), or $I_C = I_B h_{fe}$. The collector current variations represent the signal current output of the transistor. The base current is much smaller than the collector current. This is true of both the no-signal currents and the signal currents. Because a small input signal (V_{IN}) controls a large output signal (V_{OUT}), these circuits provide gain, or amplify. The common-emitter circuit is capable of both high current and high voltage gains, and therefore has the highest power gain.

In describing the operation of transistor circuits, the terms "resistance" and "impedance" are sometimes used interchangeably. However, due to the characteristics of transistor circuits, the term "impedance" is more correct than "resistance."

The COMMON-EMITTER CIRCUIT PROVIDES A MODERATE INPUT IMPEDANCE AND A FAIRLY HIGH OUTPUT IMPEDANCE.

The circuit has a moderate input impedance because only base current can exist in the forward biased base-emitter junction of the input. The fairly high output impedance is determined primarily by the practical loading considerations of the output.

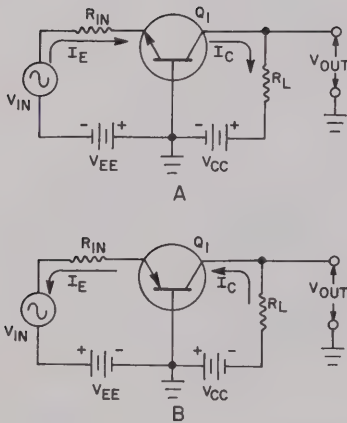


Figure
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Figures 2A and 2B illustrate **COMMON-BASE (CB) AMPLIFIER** circuits. Figure 2A shows an NPN circuit and Figure 2B shows a PNP circuit. In the common-base circuit, the input signal causes variations in the emitter current, I_E . Since the emitter current is equal to the sum of the collector current and the base current ($I_E = I_B + I_C$), the collector current is always less than the emitter current. Since variations of collector current are slightly smaller than variations of emitter current, a common-base amplifier has a current gain of slightly less than 1. Although the current gain is a little less than 1, the common-base amplifier can provide satisfactory voltage and power gains.

THE COMMON-BASE CIRCUIT PROVIDES A LOW INPUT IMPEDANCE AND A HIGH OUTPUT IMPEDANCE. The circuit has a low input impedance because emitter current must exist in the forward-biased base-emitter junction of the input. The high output impedance is primarily because of the reverse-biased collector-to-base junction of the output. The low input impedance and high output impedance of a common-base amplifier make the circuit well suited for matching low impedance sources to high impedance loads.

Figures 3A and 3B illustrate **COMMON-COLLECTOR (CC) AMPLIFIER** circuits. Figure 3A shows an NPN circuit and Figure 3B shows a PNP circuit. Again, base current plus collector current equals emitter current, as shown by the arrows representing circuit current. The input signal causes variations of base current. The variations of base current cause variations in emitter current, with the emitter current variations serving as the output. This amplifier is also called an emitter follower.

The voltage gain of a common-collector amplifier is always slightly less than 1. However, a common-collector amplifier can provide high current and is therefore often used as a power amplifier. THE COMMON-COLLECTOR CIRCUIT PROVIDES A HIGH INPUT IMPEDANCE AND A LOW OUTPUT IMPEDANCE. For this reason, the circuit is widely used to match a high input impedance to a low output impedance. Both the high input impedance and the low output impedance are due primarily to the large amounts of negative feedback that are characteristics of common collector circuits.

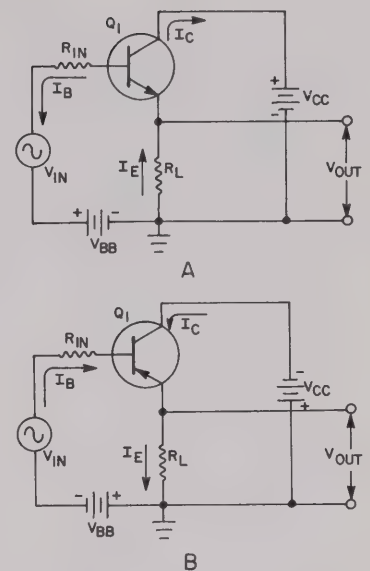


Figure 3

CIRCUIT CONFIGURATION	CHARACTERISTICS
COMMON EMITTER (CE)	LOW INPUT IMPEDANCE (1 kΩ) HIGH OUT PUT IMPEDANCE (50 kΩ) HIGH CURRENT GAIN (35) HIGH VOLTAGE GAIN (300) HIGHEST POWER GAIN (10,000)
COMMON BASE (CB)	LOWEST INPUT IMPEDANCE (30Ω) HIGHEST OUT PUT IMPEDANCE (1 MΩ) ALMOST UNITY CURRENT GAIN (.98) HIGH VOLTAGE GAIN (300) MEDIUM POWER GAIN (300)
COMMON COLLECTOR (CC)	HIGHEST INPUT IMPEDANCE (350 kΩ) LOWEST OUT PUT IMPEDANCE (500Ω) HIGH CURRENT GAIN (36) ALMOST UNITY VOLTAGE GAIN (.98) LOWEST POWER GAIN (35)

Figure 4

It is possible to obtain almost any characteristic that might be required with these three types of circuits: common-emitter, common-base or common-collector. Not only can voltage, current or power amplification be obtained, but the amplifiers may also be used as impedance-matching devices between sources and loads. The chart of Figure 4 summarizes the characteristics of the three circuits. The values of impedance and gain are for a typical small-signal transistor amplifier.

VOLTAGE PHASE REVERSAL

The phase relationship between the input and output voltages of an amplifier is very important. In some amplifier circuits, the output voltage becomes more negative as the input voltage becomes more negative, and becomes more positive when the input voltage becomes more positive. When the input and output are in step with each other, there is no phase shift between input and output signals.

In other amplifier circuits, the output voltage becomes more negative as the input voltage becomes less negative, and vice versa. Here, the output voltage signals are out of step or out-of-phase with the input, and there is a phase reversal, or a 180° phase shift between input and output.

The phase relationships of input and output voltages for each of the three basic amplifier circuits are the same, regardless of whether the transistor is a PNP type or an NPN type.

Figures 1A, 2A and 3A are NPN transistor amplifier circuits. Let's begin our discussion of voltage phase relationships by examining the common-emitter circuit of Figure 1A.

Suppose that we apply an increasing positive signal voltage to the transistor base. This increases the forward bias across the emitter-to-base junction, and collector current increases. As shown by the collector current arrow, I_C is downward through resistor R_L . The voltage developed by I_C makes the top end of R_L negative with respect to its bottom end. This signal voltage subtracts from the voltage of V_{CC} so that the collector-to-emitter voltage, V_{CE} , of Q_1 (the output voltage) is the difference between V_{CC} and the voltage across R_L , V_{R_L} . As the voltage across R_L increases, the output voltage decreases. As the signal voltage swings negative, the forward bias decreases. This decreases base current, which decreases collector current. The decreased collector current reduces the voltage drop across R_L , and causes the output voltage to become more positive. In a common-emitter circuit, an increasing

positive input change causes a decreasing positive output voltage change. The output is therefore out-of-phase with the input.

THE COMMON-EMITTER AMPLIFIER CIRCUIT PRODUCES A 180° VOLTAGE PHASE REVERSAL.

Figure 5 shows the phase relationship between the voltages and currents in the common-emitter circuit.

An increasing positive voltage at the input of an NPN transistor in a common-emitter circuit increases the forward bias of the emitter-to-base junction. An increasing positive voltage at the input of a PNP transistor (in a similar circuit) causes a reduction of forward bias, or possibly even a reverse bias of the emitter-to-base junction. Don't forget the basic difference in current direction between the NPN and the PNP types, as shown by the current arrows in Figures 1 through 3.

Figure 1B shows the PNP equivalent of the common-emitter circuit of Figure 1A. In Figure 1B, an increasing positive input voltage decreases the forward bias of the emitter-to-base junction. Collector current decreases, reducing the voltage across R_L . The top end of R_L is positive with respect to the bottom end. Because of the series-opposing arrangement, the output is the difference between the voltage across R_L , V_{R_L} , and the voltage of V_{CC} . When the voltage across R_L decreases, the output voltage increases (becomes more negative). Figure 6 shows the phase relation between the voltages and currents in the PNP common-emitter circuit. Although the directions of current and voltage polarities are different than in the NPN circuit represented by Figure 5, the phase relationships are the same.

A positive input voltage change produces a negative output voltage change. The PNP transistor connected in a common-emitter circuit provides a 180° voltage phase shift, as did the NPN transistor in a common-emitter circuit.

In the common-base amplifier circuit of Figure 2A, an increasing positive input signal voltage increase tends to decrease the forward bias on the emitter-to-base junction of the transistor. This decreases the collector current, which in turn decreases the voltage across R_L .

The voltage across R_L is series-opposing with the collector supply, V_{CC} , and the output voltage is therefore the difference between the voltage across R_L , V_{R_L} , and the voltage of V_{CC} . With a positive input voltage, there is less

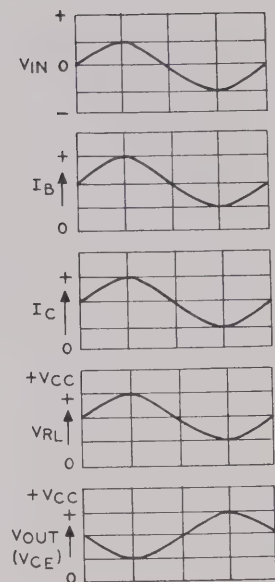


Figure 5

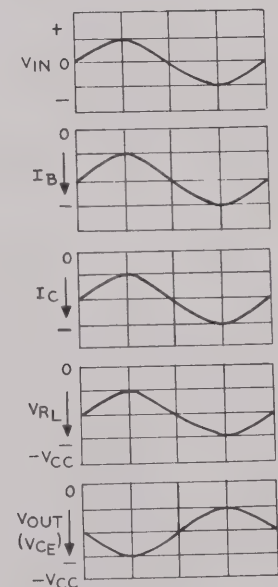


Figure 6

voltage across R_L to subtract from the V_{CC} voltage, and the output voltage becomes more positive. As the input signal goes negative, it increases the forward bias on Q_1 , and as a result, the base and collector currents increase. This increases the voltage drop across R_L and causes the output voltage to become less positive. In a common-base circuit, the input and output voltages are in phase.

THE COMMON-BASE AMPLIFIER DOES NOT PRODUCE A VOLTAGE PHASE REVERSAL.

The action is the same for the PNP circuit of Figure 2B. The only difference is the direction of current and the polarity of the voltages.

In the common-collector circuit of Figure 3A, positive input voltage causes the transistor to conduct more current, resulting in a larger voltage across R_L . This voltage serves as the output signal.

A positive input voltage causes the voltage across R_L , V_{R_L} , to become more positive. A negative input voltage decreases the conduction of the transistor and results in a decrease in the voltage across R_L . In a common-collector circuit, a positive input voltage causes an increasing positive output voltage, and a negative input voltage causes a decreasing positive output voltage.

THE COMMON-COLLECTOR AMPLIFIER DOES NOT PRODUCE A VOLTAGE PHASE REVERSAL.

The action is the same for the PNP circuit of Figure 3B. The only difference is the direction of current and the polarity of the voltages. The common-collector amplifier is also called an EMITTER FOLLOWER since the output signal is taken from the emitter and is the same phase as the input signal.

There is phase inversion (or reversal) between the input and output signal voltages of PNP and NPN transistors only in the CE circuit. All signals in the CC and CB circuits are in phase when either PNP or NPN transistors are used.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

VOLTAGE AND POWER AMPLIFIERS

TRANSISTOR AMPLIFIER TYPES

VOLTAGE PHASE REVERSAL

1. Explain the difference between a power amplifier and a voltage amplifier.
2. What is the gain of a voltage amplifier if an input signal of .5 volt develops a 10-volt output signal?
3. What is the power output of a power amplifier with a power gain of 12 if the input signal is .3 watt?
4. Which of the three amplifier configurations would you employ if you wanted to match a high source impedance to a low load impedance?
5. The highest power gain is provided by the common-_____ amplifier circuit.
6. Draw the circuits for a PNP common-emitter amplifier and an NPN common-collector amplifier.
7. Explain what happens to the various currents and voltage drops in the circuit of Figure 1A when the input signal makes the base of Q_1 less positive.

8. What is the phase relationship between the input and output signal voltages in the circuit of Figure 1A?
9. What is the purpose of resistor R_L in the circuit of Figure 1A?
10. What is the phase relationship between the input signal voltage and the collector current in a PNP common-emitter circuit?
11. As the input voltage signal drives the base more negative in a PNP common-emitter circuit, the output voltage becomes (more) or (less) negative.
12. How would you express a common-emitter circuit output voltage, V_{OUT} , in terms of the voltage drop across R_L and V_{CC} , as an equation?
13. What is the phase relationship between the input and output voltage signals in a common-base amplifier and in a common-collector amplifier?
14. How is the output voltage signal developed in a common-collector amplifier?
15. In the common-base amplifier, is the output voltage the difference between the collector supply and the voltage drop across R_L ?

BIAS CIRCUITS

The base bias of a transistor is defined as the value of the base current under zero signal or dc conditions. The dc voltage which causes base bias current is called the base bias voltage. The term bias is also sometimes applied to the collector supply voltage. However, we shall use the term "bias" to describe the value of no-signal base current or voltage. In Figures 1 through 3, batteries were used to supply bias voltages. V_{BB} supplies the base bias voltage, and V_{CC} is the collector supply. For proper operation, the transistor must be biased so that the emitter junction is forward biased and the collector junction is reverse biased. Let us assume in this discussion of bias circuits that the signal source has a large series capacitor in its output so that there is no dc flow through the input connections of the amplifiers, and the bias voltages are not affected by the signal source.

Fixed Bias

The separate supplies shown in Figures 1 through 3 provide a means of obtaining the correct bias. However, separate supplies are costly, and it is more convenient to use one supply for both the base bias and the collector supply. The circuit of Figure 7 provides a simple means of obtaining base bias from the collector supply. In this common-emitter amplifier, resistor R_1 is the bias resistor. R_1 is connected between the negative terminal of the collector supply battery, V_{CC} , and the base of Q_1 .

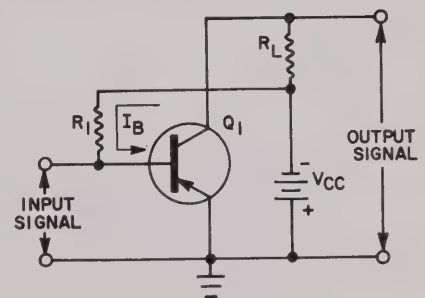


Figure
7

Since Q_1 is a PNP transistor, the base must be negative with respect to the emitter to forward bias the emitter junction. In Figure 7, R_1 connects the base of Q_1 to the negative terminal of V_{CC} . The positive terminal of V_{CC} is connected to the emitter. V_{CC} forward biases the emitter junction and reverse biases the collector junction. The value of base current, I_B (bias), is approximately equal to V_{CC} divided by the value of R_1 . The base-to-emitter voltage drop is relatively constant and can be ignored for this part of the explanation. Increasing the value of R_1 decreases the bias, and decreasing the value of R_1 increases the bias. Since the value of bias is determined by the values of V_{CC} and R_1 , both of which are fixed, the circuit is referred to as a **FIXED BIAS** arrangement. If an NPN transistor were substituted for Q_1 , the only circuit change necessary would be to reverse the collector supply battery, V_{CC} .

The impedance of the base-to-emitter junction does vary with the input signal. This causes a change in the amount of base current, and as a result, a shift in the operating point. The bias supplied by this type of circuit is not stable. Temperature variations also cause a shift in the bias. This is due primarily to collector-to-base leakage current, which acts as base current

as it passes across the base-to-collector junction. An increase in transistor temperature causes leakage current to increase. The stability of the circuit of Figure 7 is poor because all of the dc component of the current through R_1 flows into the base of Q_1 .

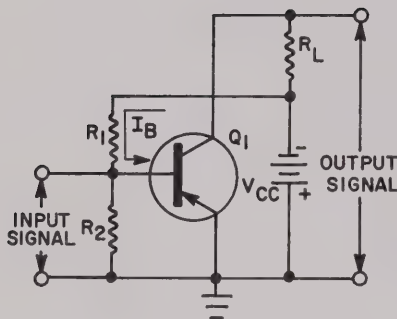


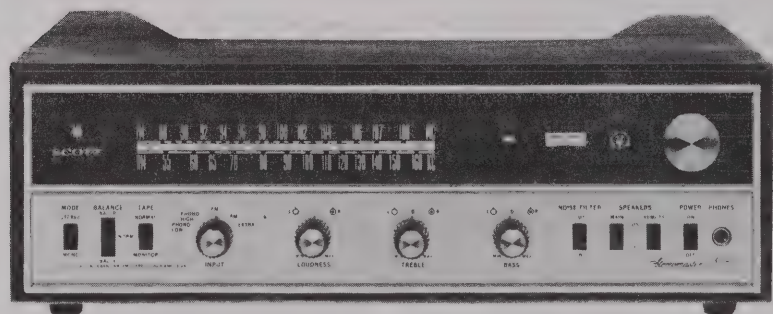
Figure 8

Voltage Divider Bias

The stability of the simple bias circuit of Figure 7 can be improved by the addition of a resistor from base to ground, as shown in Figure 8. This circuit is generally referred to as a **VOLTAGE DIVIDER BIAS** arrangement, since R_1 and R_2 form a voltage divider connected across V_{CC} .

Resistor R_2 is in parallel with the emitter-base junction of Q_1 . Thus, two current paths result: One is from the — terminal of V_{CC} through R_1 and R_2 to the + terminal of V_{CC} , and the other is from the — terminal of V_{CC} through R_1 and the emitter-base junction of Q_1 to the + terminal of V_{CC} .

To examine circuit operation, assume that base current increases due to an increase in temperature. The increased base current through R_1 increases the voltage across R_1 , which decreases the voltage drop across R_2 . Since the voltage drop across R_2 establishes the bias on Q_1 , the forward bias is reduced. This tends to return the base current to its original value. If base current decreases, the voltage drop across R_2 increases, which increases the forward bias on Q_1 and returns the base current to its original value.



The audio amplifier stages in FM receivers like the one shown above often employ a feedback bias arrangement to provide good stability and wide frequency response.

Courtesy H. H. Scott

The value of R_2 in this circuit is very critical. Suppose that we choose a large resistance — perhaps 500 k Ω or 1 megohm — for R_2 . Then the resistance of the parallel combination of R_2 and the Q_1 base-to-emitter junction is essentially that of the junction, which is very small compared to a 500 k Ω or 1 megohm resistor. R_2 has little effect, and the circuit behaves similar to the circuit of Figure 7.

On the other hand, suppose that we choose R_2 to be a very low resistance. Notice, in Figure 8, that R_2 is directly across the input terminals. Making R_2 smaller stabilizes the bias, but it also shunts most of the input signal applied to the circuit, because now the input impedance is very low.

The value of R_2 must be selected to be between these two extremes. The value chosen depends on the input impedance characteristics of the transistor used and the amount of base current desired. When the value of R_2 is such that the current through it is several times the base current, the voltage across this resistor remains fairly constant. Consequently, the circuit of Figure 8 has a more stable operating point than the circuit of Figure 7, and it still uses only one battery for both base and collector bias.

Feedback Bias Circuit

Although the circuit of Figure 8 provides some bias stability, improved stability can be obtained by employing a bias circuit with CURRENT FEED-BACK. The effects of temperature changes on base current and collector current may be shown with the aid of Figures 9 and 10. A typical transistor operating at normal operating temperature in a common-emitter circuit will have a family of collector characteristic curves similar to those shown in Figure 9. Suppose that the operating temperature of the transistor is increased. With a given value of collector voltage and base current, the collector leakage current increases as the temperature increases. This causes the internal resistance of the transistor to decrease. Since the resistance of the base-to-emitter junction also decreases, the base current increases. These current increases cause the base current lines of Figure 9 to shift upward and spread apart somewhat, as shown by Figure 10. This means that the current gain of the transistor increases.

To counteract the increase of base current caused by temperature increases, degenerative (or negative) feedback may be added to the transistor circuit. This means that a part of the output signal is fed back to the input 180° out-of-phase with the input signal.

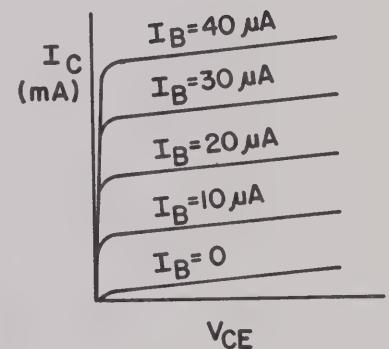


Figure 9

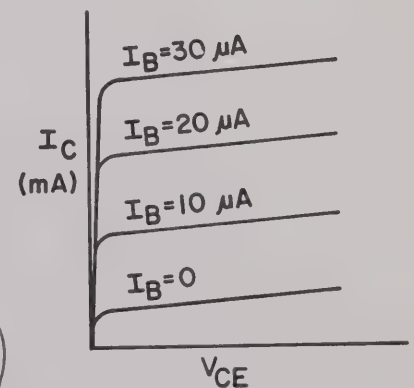


Figure 10

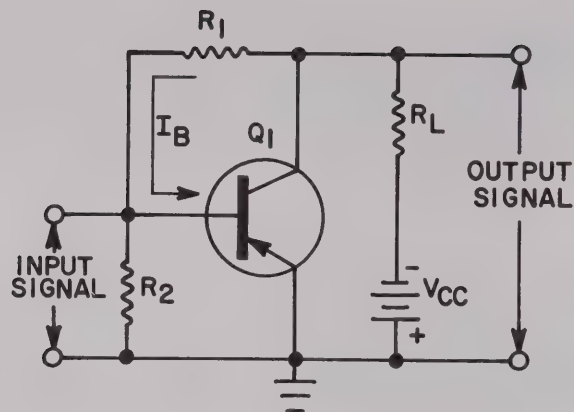


Figure 11

A method of obtaining negative feedback is shown in Figure 11. The R_1R_2 bias circuit is connected directly to the collector and produces base current I_B in the direction shown. As the temperature of the transistor increases, the collector current increases, as illustrated by the shift of the characteristic curves of Figure 10. With increased collector current, the voltage across the collector load resistor, R_L , increases. With an increased voltage across R_L , the collector voltage decreases. Since the bias circuit is connected to the collector, the reduced collector voltage causes a decrease in base bias current I_B . This tends to bring the base current back to its original value, thus counteracting the effects of the temperature change. Therefore, the circuit provides voltage feedback since the base current and voltage are controlled by the collector voltage.

If the transistor is not protected, it may continue to conduct more and more current, and soon overheat. This is called thermal runaway. If this action is allowed to continue, the transistor may be permanently damaged. This circuit not only protects against thermal runaway but also stabilizes against any other variations in circuit operation.

A disadvantage of negative feedback is that it reduces the gain of the amplifier. That is, it feeds a signal back to the input of the transistor which effectively reduces the size of the input signal. In many cases, the stability obtained with the circuit more than compensates for the gain reduction, and this biasing method is often used in amplifiers.

Figure 12 shows an amplifier with voltage divider bias and degenerative current feedback. R_1 and R_2 provide voltage divider bias, and R_3 provides the current feedback. The amount of feedback provided by R_3 is determined

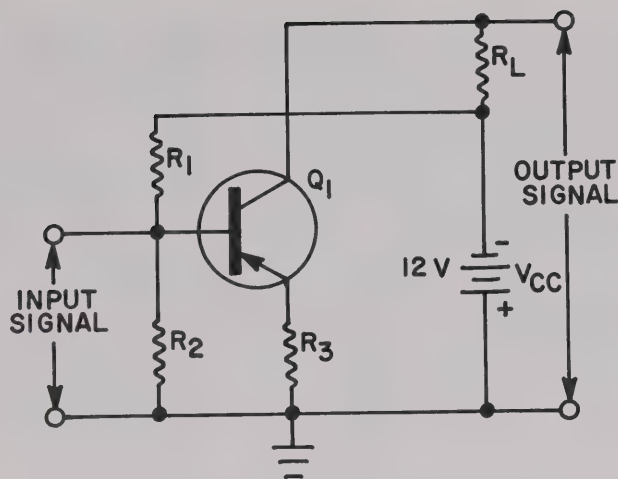


Figure 12

by its resistance value and by the emitter current. The feedback helps to keep the bias constant as temperature changes, and therefore aids in preventing thermal runaway.

The negative feedback is produced because of the voltage drop developed across R_3 . The signal at the base of Q_1 causes signal current through the transistor. The resultant signal voltage across R_3 is in phase with the signal at the base. This causes feedback whose amount is proportional to the resistance value of R_3 . The voltage drop developed across R_3 is also proportional to the amount of collector current, and this drop therefore serves to limit, or regulate, collector current. Therefore, the amplifier of Figure 12 requires a larger input signal for a given output signal than does the amplifier of Figure 8.

Should the transistor heat up, its internal resistance decreases and the collector current becomes larger. The increase in collector current tends to reduce the forward bias on the emitter junction because of the larger voltage drop across R_3 , and therefore decreases the conduction of Q_1 . In this way, the circuit is stabilized, and the possibility of thermal runaway is reduced.

If the negative feedback provided in the circuit of Figure 12 is not required, the arrangement shown in Figure 13 may be used. The circuit of Figure 13 is the same as the circuit of Figure 12, except that capacitor C_1 is placed in parallel with R_3 . This is done to prevent the voltage across R_3 from varying with the input signal, so that the voltage gain is now substantially increased. For low-frequency signals, the reactance of C_1 is so low that it effectively bypasses the collector signal current variations of the amplifier.

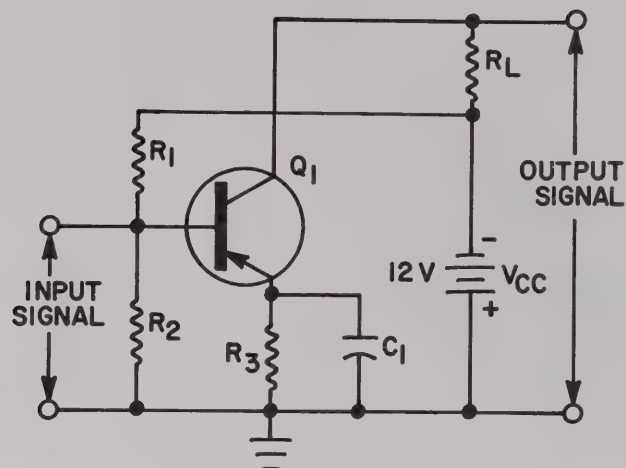


Figure 13

The value of C_1 is chosen so that its reactance is $1/10$ the value of R_3 at the lowest frequency to be amplified. Resistor R_3 now provides only dc feedback for stabilization.

The voltage gain of the circuit of Figure 13 is approximately equal to R_L divided by R_3 . For example, if R_L is 2200 ohms and R_3 is 220 ohms, then:

$$A_v = \frac{R_L}{R_3} = \frac{2200}{220} = 10.$$

The voltage gain is about 10 if β is sufficiently high (many times greater than 10).

Transistor Type Identification

As mentioned earlier, when the emitter junction is forward biased, it has a very low impedance. Although this impedance is low, a definite voltage drop exists across the base-to-emitter junction. The exact value depends upon the circuit, but as a rule, the forward biased base-emitter voltage, V_{BE} , of a germanium transistor is about .2 to .3 volt, while that for a silicon transistor is about .6 or .7 volt. You can use the base-to-emitter voltage drop to determine whether a transistor is germanium or silicon if data is not available for the transistor being tested.

Knowing the range of base-to-emitter voltage drops is very important, especially when servicing different types of equipment. Care must be exercised when interpreting voltage readings, as they are often given with respect to ground, and as a result, the base-emitter voltage must be calculated. For example, examine the voltages in Figure 14A. Note that both the base and emitter voltages are negative. However, the emitter is more negative than the base, thus establishing the correct bias for the NPN transistor. Since the bias voltage (V_{BE}) in this example is .2 volt, we can assume that the transistor is germanium. In Figure 14B, the base is more negative than the emitter. Because the transistor is a PNP type, this provides the correct forward bias. Since the bias voltage, V_{BE} , is .7 volt in this example, we can assume that the transistor is silicon.

CLASSES OF OPERATION

The CLASS OF OPERATION of a transistor amplifier is determined by THE LENGTH OF TIME THAT THE COLLECTOR CURRENT FLOWS DURING THE INPUT CYCLE. If there is collector current during the entire input cycle, the operation is Class A. In Class B operation, there is collector current for approximately half the input cycle. In Class C operation, there is current for less than half of the input cycle. In Class AB operation, there is collector current for more than half of the input cycle, but not for the full cycle.

Class A operation produces the least amount of distortion. Class B operation produces a greater amount of distortion, and Class C produces the greatest amount of distortion. Since the distortion produced in Class C amplifiers cannot be tolerated in most low-frequency applications, Class A or Class B operation is preferred.

Class A Operation

The circuit of a basic **CLASS A AMPLIFIER** is shown in Figure 15. Battery V_{BB} supplies the base bias voltage which sets up the desired base current. V_{CC} supplies the collector with the proper operating voltage. The input signal voltage causes the base current, i_B , to increase and decrease according to the input signal level. It is understood that the input signal source does not offer a path for dc current that will disturb the no-signal base bias. Therefore, the operating point is not affected by the input signal source.

For Class A operation, the transistor must be biased so that collector current exists during the entire input signal cycle. Generally, transistors in Class A amplifiers operate only on the linear or straight portion of their character-

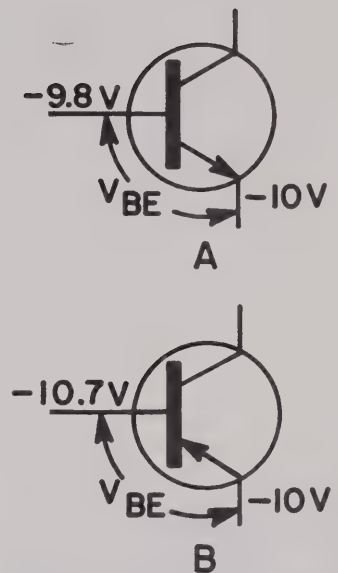


Figure
14

istic transfer curves. Therefore, such Class A amplifiers are called **LINEAR AMPLIFIERS**. To illustrate this class of operation, the base current-collector current, I_B - I_C , transfer characteristic curve for the circuit of Figure 15 is shown in Figure 16. This curve shows how collector current depends upon base current.

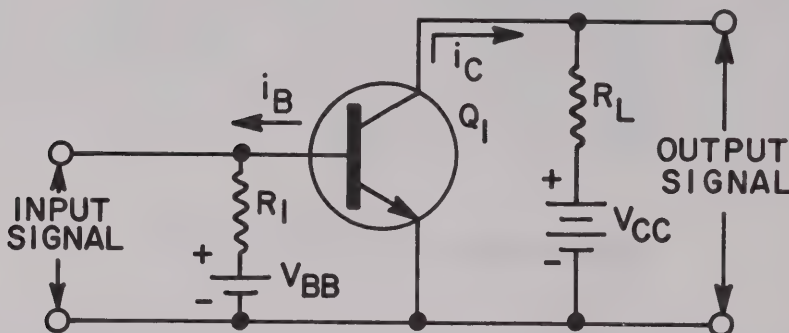


Figure 15

Point Q in Figure 16 is the operating point. This is the point of operation with no input signal. It is centered approximately in the straight or linear part of the curve. When a signal is applied, the current varies up and down this curve, but not beyond the straight portion of the curve.

The input signal in Figure 15 produces a base current change, Δi_B , of 20 μA peak-to-peak, or 10 μA peak. This alternating current, i_B , is shown at the bottom of Figure 16. This causes the base current to vary up and down the operating curve from the operating point Q (25 μA). The bias battery, V_{BB} , produces 25 μA of base current for no-signal conditions. The generator produces an alternating current which causes the total base current to vary from 15 μA to 35 μA . By projecting these values of base current of Figure 16 up to the curve, points A and B are located. These points represent the extremes of operation on the curve.

As base current in Figure 16 increases from the operating point value of 25 μA to 35 μA , collector current increases from 3 mA to 4.5 mA. On the opposite alternation of i_B , the base current decreases to 15 μA , which causes a corresponding decrease in collector current from 3 mA to 1.5 mA. As the base current increases 10 μA above and below the operating point, the collector current varies 1.5 mA above and below its operating point. Therefore, the collector current varies in direct proportion to the base current. This is the requirement for linear operation.

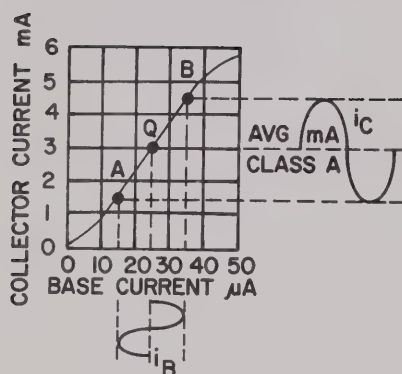


Figure 16

BIAS CIRCUITS

VOLTAGE DIVIDER BIAS

FEEDBACK BIAS CIRCUIT

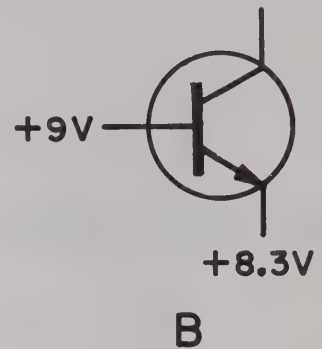
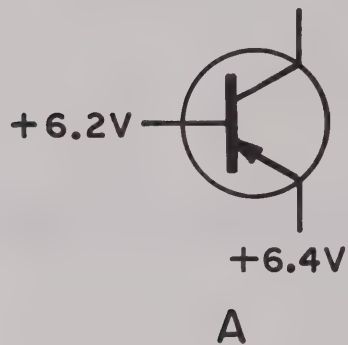
TRANSISTOR TYPE IDENTIFICATION

- 1079
-
- Q2

18. Draw a voltage divider bias circuit employing an NPN transistor.
19. In Figure 8, what happens to the voltage drop across R_2 if base current increases?
20. What is the advantage of making R_2 in Figure 8 as small as possible?
As large as possible?
21. Draw a voltage feedback bias arrangement, similar to the one shown in Figure 11, with an NPN transistor.

22. Explain how the bias arrangement of Figure 11 maintains a constant bias when a decrease in temperature causes a decrease in the collector and base currents.
23. In Figure 13, if R_L is $10\text{ k}\Omega$ and R_3 is 2700Ω , what is the voltage gain?
24. Draw a circuit similar to the one shown in Figure 13 for an NPN transistor.

25. An increase in the voltage developed across R_3 in Figure 13 increases forward bias on the emitter junction. True or False?
26. In the figures below, determine the actual base-to-emitter voltage and determine whether the transistors are silicon or germanium.





Where high-fidelity operation is required, such as in the amplifiers in a tape recorder, Class A operation is employed.

Courtesy Bell & Howell

Earlier in this lesson, we stated that a common-emitter amplifier provides a high current gain. Since Figure 15 is a common-emitter amplifier, let us find its current gain. Current gain is the ratio of the output current change to the input current change. In the circuit of Figure 15, a $20\ \mu\text{A}$ change in base current, Δi_B , produces a $3\ \text{mA}$ ($3000\ \mu\text{A}$) change in collector current, Δi_C . The current gain, A_I , therefore equals:

$$A_I = \frac{\Delta i_C}{\Delta i_B} = \frac{3000}{20} = 150.$$

The circuit of Figure 15 provides a current gain of 150. This means that any small change in base current will produce a change in collector current 150 times greater, as long as the operation is on the linear portion of the transfer characteristic curve.

TRANSISTOR LOW-FREQUENCY AMPLIFIERS

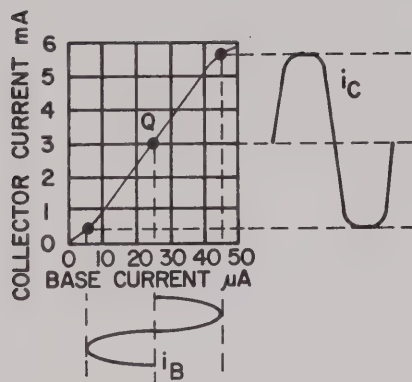


Figure
17

Distortion in a Class A amplifier usually is a result of too large an input signal or a shift in the operating point due to bias changes. The following conditions will occur with an input signal that is too large. Suppose that the input signal in the circuit of Figure 15 is increased to produce a base current change of 20 μA peak. This condition is shown on the characteristic curve of Figure 17.

Projecting the i_B values on the transfer characteristic curve shows that, for a 20 μA increase in base current, the collector current increases from 3 mA to 5.7 mA. A decrease in the base current of 20 μA results in a collector current decrease of 2.7 mA (from 3 mA to .3 mA). The collector current increases 2.7 mA and decreases 2.7 mA for equal changes in base current.

There is a definite flattening of the collector current waveform peaks of Figure 17 due to operation near cutoff and saturation. Cutoff describes the point where the transistor does not conduct, as at the lower left end of the curve. Saturation describes the point where the transistor is conducting at its maximum possible rate, as at the upper right end of the transfer curve. If the input signal is increased to a point where it drives the transistor beyond cutoff and saturation, clipping occurs, and the output begins to appear as a squared off waveshape. The collector current waveshape is then no longer the same shape as that of the signal causing the change of base current. This condition is known as distortion. The input signal is too large and the amplifier is "overdriven."

To reduce this type of distortion, all that is required is to decrease the input signal level. A conclusion may then be drawn concerning linear Class A operation: for maximum output with minimum distortion, the input signal must not drive the transistor into the nonlinear or curved regions of its characteristic transfer curve.

The efficiency of a Class A amplifier is low (approximately 30%). The maximum possible efficiency for Class A operation is around 50%. By efficiency, we mean the signal or useful output compared to the average dc power delivered to the collector circuit. In the form of an expression, the efficiency is:

$$E_{\text{eff}} = \frac{P_{\text{OUT}}}{P_{\text{dc}}} \times 100 \quad (4)$$

where: P_{OUT} = useful output power,

P_{dc} = dc power input from the power supply, and

E_{ff} = percent efficiency.

The dc input power is generally taken as the product of the collector supply voltage and the no-signal collector current:

$$P_{dc} = I_{C(AVE)} \times V_{CC} \quad (5)$$

where: P_{dc} = dc power input from the power supply,

$I_{C(AVE)}$ = average collector current, and

V_{CC} = collector supply voltage.

For example, if 1 watt of power is delivered by the collector battery but only .25 watt of audio power is developed at the output of a given circuit, its efficiency is:

$$E_{ff} = \frac{P_{OUT}}{P_{dc}} \times 100$$

$$= \frac{.25}{1} \times 100$$

$$= .25 \times 100 = 25\%.$$

The addition of an emitter resistor reduces the efficiency of a Class A transistor amplifier even more. In spite of this poor efficiency, Class A transistor amplifiers are widely used. They are used where the power desired is not too great and where distortion cannot be tolerated. Class A amplifiers are widely used where maximum fidelity is required, such as in the audio amplifier stages of radio and television receivers, and in many high-quality test instruments.

Class B Operation

In a **CLASS B AMPLIFIER**, the transistor is biased so that collector current exists for approximately one half, or 180° , of the input signal cycle, as shown in Figure 18. The transfer curve of Figure 18 shows that, at the operating point Q, the transistor is biased approximately AT COLLECTOR CURRENT CUTOFF. THIS PRODUCES CLASS B OPERATION. The slight amount of collector current flowing with no input signal is the collector leakage current. Since the base current, i_B , cannot be less than zero, it will not go to the left of the $i_B = 0$ vertical line. It is therefore not a sinewave, even though the input signal voltage is.

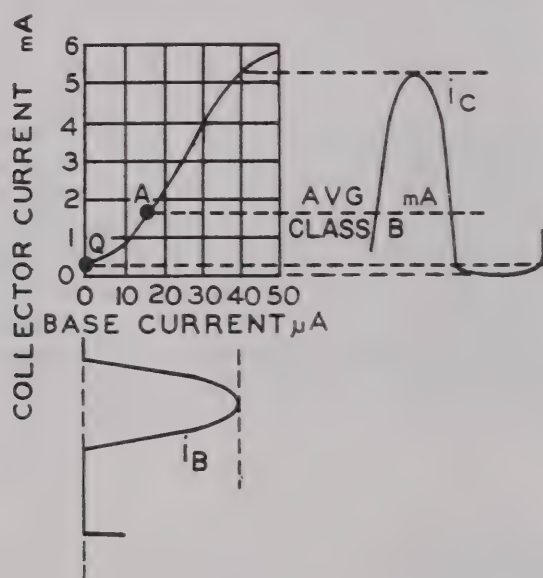


Figure 18

In this example, the input signal causes a peak i_B value of 40 μA on one alternation. On the other alternation, the input signal produces reverse bias and does not allow any collector current. The collector current has a peak value of 5.25 mA on the half cycle during which it conducts.

Since there is collector current for only about one half of the input cycle, it appears in the form of pulses. The average collector current is .318 of the peak collector current if the waveshape is a half sinewave. Using this factor of .318, the average value of collector current shown in Figure 18 is .318 $\times$

$5.25 \text{ mA} = 1.67 \text{ mA}$. This level is indicated by the dashed horizontal line passing through the curve at point A. Sometimes this level is referred to as the direct current component of collector current.

As mentioned earlier, the efficiency of an amplifier is the ratio of the ac power delivered to the load compared to the dc power taken from the power supply. Since a Class B amplifier draws power from the supply only during signal conditions, the average power delivered to the collector circuit is lower than for Class A operation. A Class B amplifier is more efficient than a Class A amplifier (which continually draws power from the supply). The maximum efficiency for Class B operation is about 78%.

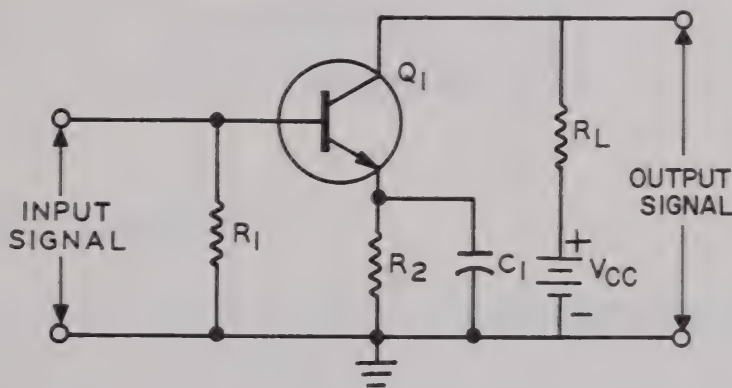


Figure 19

The amplifier shown in Figure 19 may be operated Class B. Notice that in this circuit there is no bias applied to the base of Q_1 . Therefore, this circuit is often called a zero-bias amplifier. Resistor R_2 in the emitter circuit provides thermal runaway protection. The main disadvantage of Class B operation is the distortion that it produces.

The operation of the circuit of Figure 19 may be shown by the collector-characteristic curve of Figure 20, or by a transfer-characteristic curve similar to that of Figure 18. The zero-bias conditions in the circuit of Figure 19 place the operating point, Q , at $I_B = 0$, as shown in Figure 20. On one alternation of the input signal, the base circuit is forward biased and collector current flows. The other alternation of the input signal reverse biases the base circuit and there is no collector current. Collector current exists for close to half the input cycle, satisfying the requirements for Class B operation.

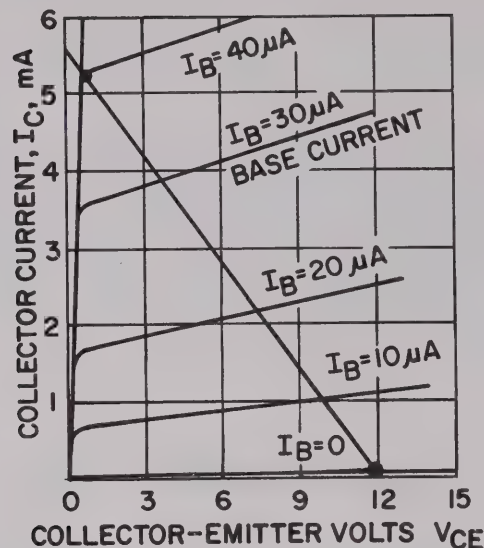


Figure 20

Class AB Operation

For greater efficiency than can be obtained with Class A amplifiers, **CLASS AB AMPLIFIERS** may be used. Class AB operation requires that there be collector current for more than half but less than the full input cycle. For Class AB operation, the transistor is biased between cutoff and the center of the linear portion of its characteristic curve. This arrangement also permits the use of a larger input signal. The circuit of Figure 15 can represent Class AB operation, as well as Class A. The transfer characteristic curve of Figure 21 is for Class AB operation of the circuit. Suppose that R_1 has a value that provides a base bias of $15 \mu\text{A}$. This causes the circuit to operate at point Q on the transfer curve of Figure 21. Suppose that the input signal results in a peak i_B value of $30 \mu\text{A}$. Collector current flows the entire positive alternation, but only partly in the negative alternation. There is no base current between A and B on the base current, i_B , curve and no collector current between A' and B' on the collector current i_C curve. The transistor conducts for about two-thirds of the input cycle. The resulting output signal, i_C , is shown at the right side of Figure 21.

Class AB operation produces distortion because it does not reproduce the complete input cycle, but the distortion is less than with Class B. The efficiency is greater than with Class A but less than with Class B operation.

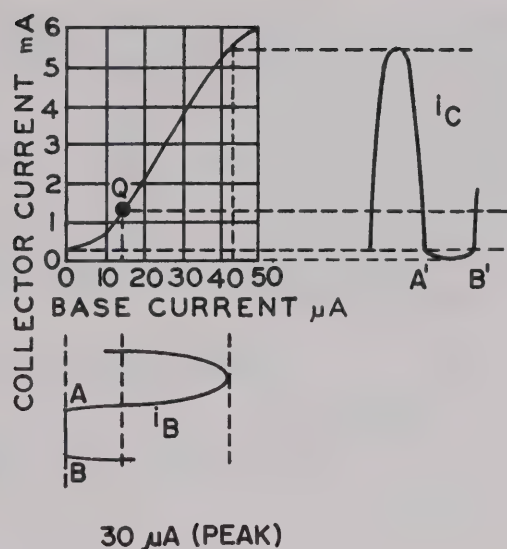


Figure 21

Class C Operation

Where a very high efficiency is desired and a large amount of distortion can be tolerated, **CLASS C AMPLIFIERS** are used. Most oscillators with tuned circuits, which are simply modified forms of amplifiers, operate Class C. Another common use for Class C operation is in the r-f amplifiers of transmitters. Class C operation is most often used with resonant circuit loads which help smooth out the distorted waveshapes and where peak signal amplitudes do not change.

In Class C operation, the transistor is biased well beyond cutoff so that there is collector current for significantly less than half of the input cycle, and it appears in the form of pulses. Within reasonable limits, the bias can be any value beyond collector current cutoff. Experience has shown that a bias level well beyond the cutoff value produces the best efficiency.

The operating point is considerably to the left of the point in Figure 22 where I_B is zero. The input signal voltage level must be large enough to overcome the cutoff bias value so that there is collector current during a small part of each cycle of the signal.

Class C operation is the most efficient because the transistor draws power from the battery or power supply for the shortest period of the input signal cycle.

TRANSISTOR LOW-FREQUENCY AMPLIFIERS

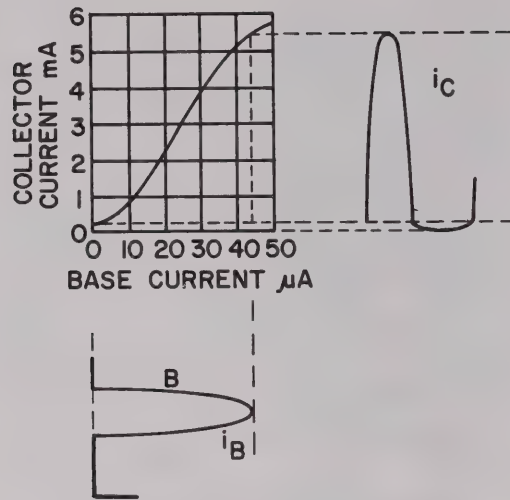


Figure 22

Under certain conditions, Class C efficiency may be as high as 85%. Keep in mind, though, that this short conduction period results in an output with a great deal of distortion and is not suitable for many applications.

There is some disagreement within the electronics industry as to whether a zero-bias transistor amplifier is operating Class B or Class C. The point in question revolves around the approximately .2- or .6-volt drop required to forward bias the base-emitter junction of a transistor. For true Class B operation, the amplifier should conduct through a complete 180° half cycle of the input signal. However, because of this voltage drop, a zero-bias transistor amplifier will conduct for a little less than the full 180° conduction required for Class B operation. Strictly speaking, this would be called Class C operation. However, an argument is given that Class C operation is really thought of as being just a portion of the most extreme peak of the input signal. Thus, Class C operation would then be redefined as considerably less than 180° conduction.

METHODS OF COUPLING

Although a single transistor can provide a large gain, it is often necessary to have more gain than one transistor amplifier stage can develop. More gain may be achieved by COUPLING two or more stages together. The output of one stage is applied to the input of a second stage and the output is taken

The following Practice Exercise questions cover the subjects which you have just studied. They are:

CLASSES OF OPERATION

CLASS A OPERATION

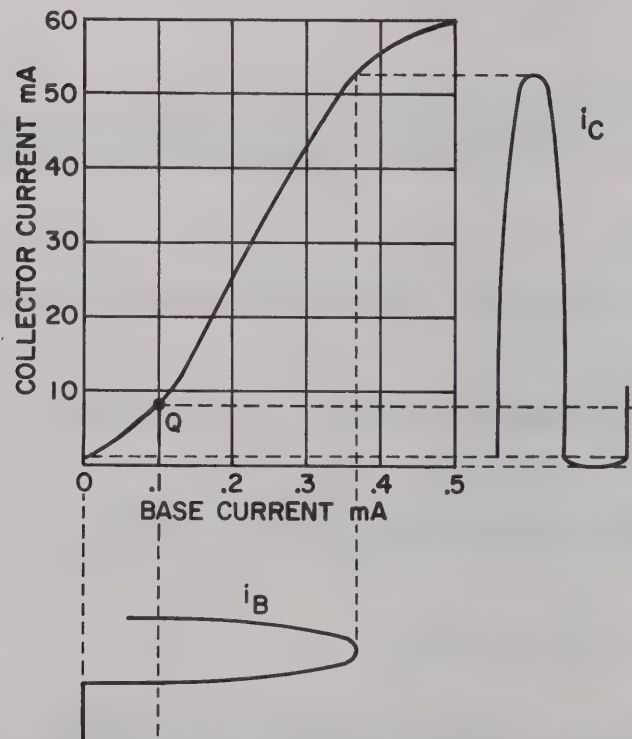
CLASS B OPERATION

CLASS AB OPERATION

CLASS C OPERATION

27. What is a Class A amplifier?
28. What is the current gain of a transistor amplifier if an input signal current of $15\ \mu\text{A}$ p-p produces an output signal current change of $4\ \text{mA}$ p-p?
29. What is meant by the term efficiency with respect to an amplifier?
30. What is the approximate efficiency of a Class A amplifier?
31. Is the distortion high or low in a Class A amplifier?
32. What is a Class B amplifier?
33. Is the efficiency of a Class B amplifier greater than that of a Class A amplifier?
34. What is the maximum efficiency of a Class B stage?

35. How is a transistor amplifier biased for Class B operation?
36. What is a Class AB amplifier?
37. How does the efficiency of a Class AB amplifier compare to that of a Class A and of a Class B amplifier?
38. What is a Class C amplifier?
39. What is the maximum efficiency of a Class C amplifier?
40. What class of operation is shown in the figure below?



from the second stage, and when necessary, applied to the input of a third stage, etc. When the signal passes from one stage to another in sequence, the arrangement is called cascaded stages. The most common methods of coupling amplifier stages together are: transformer coupling, resistance-capacitance coupling, impedance coupling and direct coupling.

Transformer Coupling

Figure 23 shows an amplifier using **TRANSFORMER COUPLING**. The signal applied to the input terminals is coupled by transformer T_1 to the base of transistor Q_1 . The output of the Q_1 stage is coupled by T_2 to the second stage, and T_3 couples the Q_2 stage output to the amplifier output terminals. In this circuit, the transformers are usually of the voltage step-down (and current step-up) type.

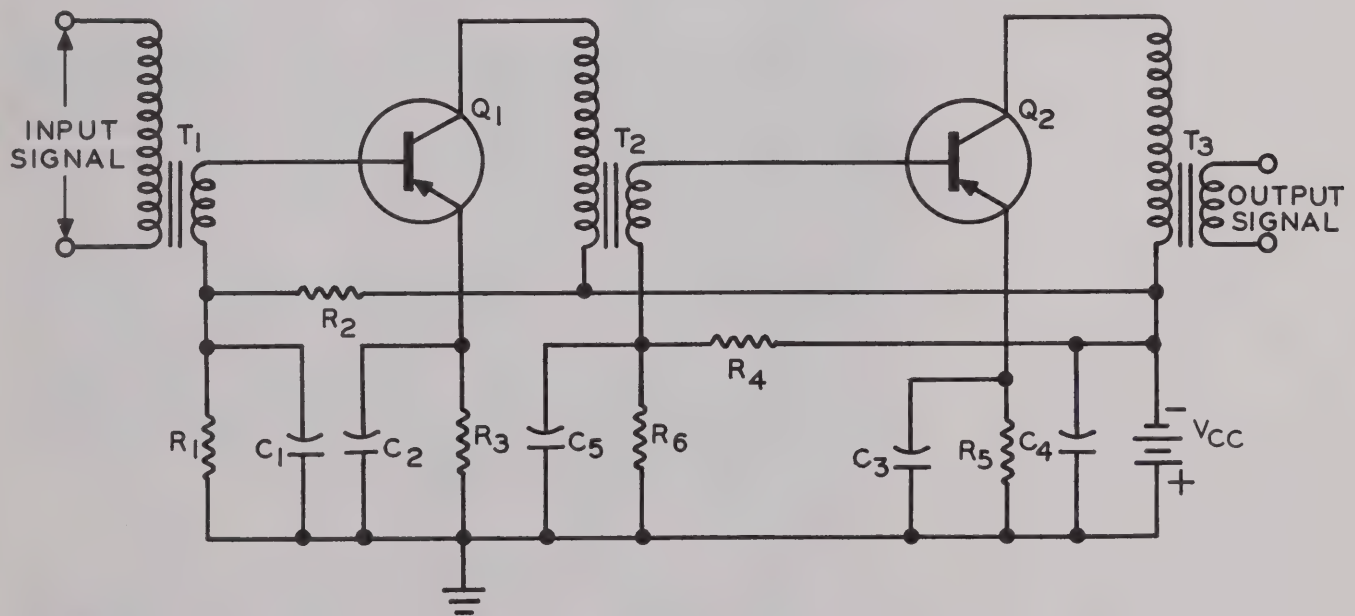


Figure 23

A single battery, V_{CC} , provides both bias and collector voltages for the circuit. The voltage at the negative terminal of V_{CC} is applied through the dc path provided by the primary winding of T_2 to the collector of Q_1 , and through the T_3 primary to the collector of Q_2 . The voltage at the junction of R_1 and R_2 is applied through the T_1 secondary winding to the base of Q_1 , for fixed bias.

Fixed bias is applied to the base of Q_2 from the junction of R_4 and R_6 through the T_2 secondary winding.

Emitter resistors R_3 and R_5 stabilize changes in the transistor biasing caused by changes of temperature or other conditions. Capacitors C_1 , C_2 , C_3 , C_4 and C_5 are bypass capacitors. Capacitor C_2 holds the emitter of Q_1 at a constant potential with respect to ground. Capacitor C_4 does the same for the emitter of Q_2 .

An alternating signal voltage at the input of the amplifier appears across the primary winding of T_1 , and induces a signal voltage into the T_1 secondary winding. This voltage is in series with the bias voltage across R_1 from the base of Q_1 to ground. The signal alternately increases and decreases the base voltage and current around its fixed bias level. This causes corresponding variations of emitter and collector current.

When the signal voltage makes the upper end of the T_1 secondary winding negative, it aids the base forward bias, which increases the base and collector currents. During the opposite alternation of the signal voltage, the signal opposes the base bias and reduces base current, which decreases the collector current.

The collector current of Q_1 varies with the signal changes at its base. The changes of Q_1 collector current are coupled through T_2 to the base of Q_2 . The resultant signal voltage varies the forward bias of Q_2 , causing an amplified version of the changes in its collector current waveform. The Q_2 collector current variations induce signal voltage in the secondary of T_3 , which is where the output of the amplifier is obtained.

The small signal applied to the input terminals is increased in magnitude as it passes through each stage. The output may be either a large signal current or a large signal voltage, depending upon the load requirements. Transformer coupling has the advantage of providing a good impedance match between the high output impedance of one stage and the low input impedance of the next stage. The transformer turns ratio is selected to provide the desired impedance match. A transformer that steps down voltage also steps down impedance. Although the voltage ratio varies with the turns ratio, the impedance ratio varies with the square of the turns ratio. As an example, assume that the CE transistors of Figure 23 have an input impedance of 1 k Ω and an output impedance of 50 k Ω (Figure 4). A transformer such as T_2 in Figure 23 would therefore require a turns ratio of:

$$N^2 = \frac{Z_1}{Z_2} \quad (6)$$

$$N^2 = \frac{50 \text{ k}\Omega}{1 \text{ k}\Omega} = 50$$

$$N = \sqrt{50} = 7.07$$

A step-down transformer with a turns ratio of 7:1 would be adequate for matching 50 k Ω to 1 k Ω . The disadvantages of transformer coupling are the expense, limitations of frequency response and the size of the transformer.

Resistance-Capacitance Coupling

Figure 24 shows an amplifier with circuit **RESISTANCE-CAPACITANCE (RC) COUPLING**. The transistors used in this circuit are NPN types. A single power supply, $+V_{CC}$, supplies bias and collector operating voltages. Resistors R_1 and R_2 provide voltage divider bias for Q_1 , and R_5 and R_6 provide voltage divider bias for Q_2 . Resistors R_4 in the emitter circuit of Q_1 and R_8 in the emitter circuit of Q_2 stabilize the circuit by controlling the forward bias on the emitter junctions of the transistors. Capacitors C_1 and C_3 are bypass capacitors. Capacitor C_2 couples the signal from the collector of Q_1 to the base of Q_2 . There may also be coupling capacitors C_{IN} at the input and C_{OUT} at the output of the two-stage amplifier. When capacitors C_{IN} and C_{OUT} are used, they replace the direct connections. When

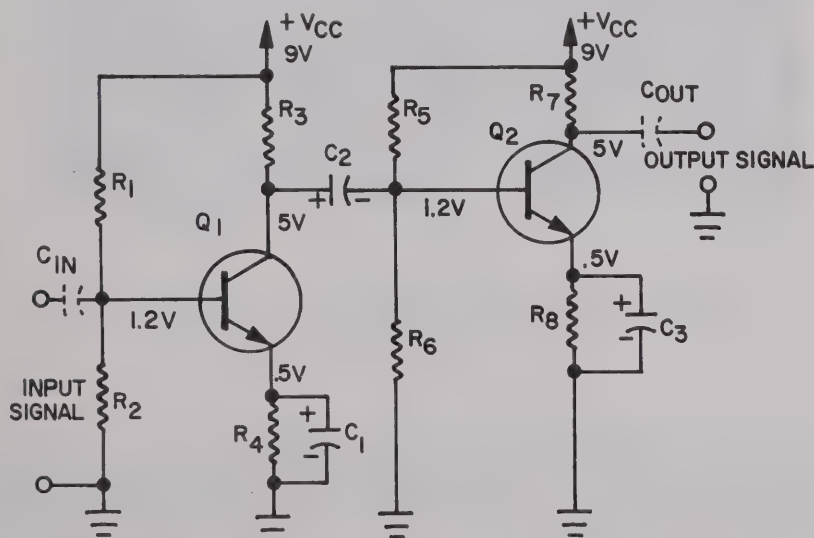
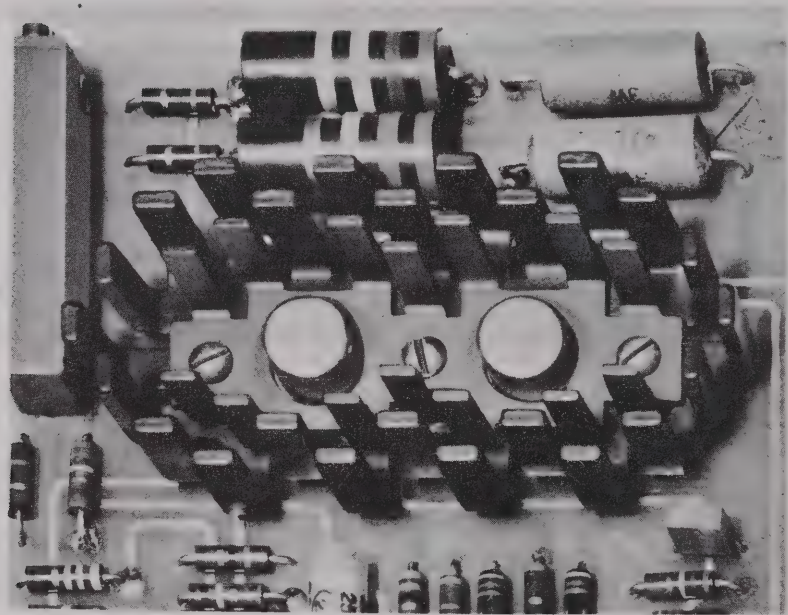


Figure 24

TRANSISTOR LOW-FREQUENCY AMPLIFIERS

C_{IN} is employed, it blocks dc from the source which could otherwise upset the bias of Q_1 . Capacitor C_{OUT} is used to isolate the dc level at the collector of Q_2 from the circuit output.

Let's first examine circuit operation under no-signal conditions. The voltage at the collector of Q_1 is 5 volts, and the voltage at the base of Q_2 is 1.2V. Note that the bias, V_{BE} , on both Q_1 and Q_2 , is .7 volt. They are therefore silicon transistors in the forward-biased condition. Under these conditions, C_2 will charge to the difference between the Q_1 collector voltage and the Q_2 base voltage, 3.8 volts. The charge paths for C_2 are through the emitter-base circuits of Q_2 , and through C_2 to $+V_{CC}$. Resistor R_6 parallels the emitter-base junction of Q_2 and carries some of the charge current, but the base-to-ground impedance through Q_2 is so much lower than the value of R_6 that the emitter carries most of the charge current.



To increase the power-handling capability of a transistor, a heat sink is often employed to pass the heat produced by the transistor into the air.

Courtesy International Electronic Research Corp.

The signal at the collector of Q_1 is coupled to the base of Q_2 by the charge and discharge of C_2 . To examine the operation, assume that a sinewave signal is applied to the base of Q_1 . Let's consider the positive alternation first. Since Q_1 is an NPN transistor, the positive signal alternation increases the forward bias, and as a result, the base current through Q_1 increases.

In turn, the Q_1 collector current increases. The increased Q_1 collector current increases the voltage drop across R_3 , which decreases the Q_1 collector voltage. With the Q_1 collector voltage reduced, C_2 starts to discharge, as it tends to remain charged to the difference between the Q_1 collector voltage and the Q_2 base voltage. The discharging of C_2 makes the base of Q_2 go in a negative direction, decreasing the forward bias on Q_2 . This decreases the base current of Q_2 , causing its collector voltage to go positive. Note the phase relations between the signals. As the input signal goes positive, the Q_1 collector voltage decreases and this negative-going signal applied to Q_2 causes its collector voltage to go more positive. Each common-emitter stage produces a 180° signal phase shift. With two stages, the output signal voltage is in phase with the input signal voltage.

When the input signal goes negative, the Q_1 base and collector currents decrease. As a result, the voltage drop across R_3 decreases, increasing the Q_1 collector voltage. This causes C_2 to charge again, increasing the Q_2 base and collector currents, which decreases the Q_2 collector voltage.

Coupling capacitor C_2 and the input resistance of Q_2 form a high-pass filter. To assure that most of the signal at the collector of Q_1 is coupled to the base of Q_2 , the time constant for C_2 and the input resistance of Q_2 must be long. As a rule, the time constant should be 10 times the period of the lowest frequency to be amplified. For example, assume that the combined input resistance of the Q_2 stage (the value of R_6 in parallel with R_3 and the Q_2 base-emitter impedance) is $1\text{ k}\Omega$ and the lowest frequency to be amplified is 100 Hz . The period of a 100 Hz signal is:

$$t = \frac{1}{f}$$

$$= \frac{1}{1 \times 10^2}$$

$$= 1 \times 10^{-2} \text{ sec, or } 10 \text{ milliseconds.}$$

The value of the time constant should be 10 times this, or $1 \times 10^{-1} \text{ sec}$ (100 milliseconds). To determine the value of C_2 , we can rearrange the RC time constant formula:

$$T = RC.$$

Divide both sides by R:

$$\frac{T}{R} = \frac{RC}{R}$$

Since $R/R = 1$, the expression reduces to:

$$C = \frac{T}{R}$$

$$C = \frac{1 \times 10^{-1}}{1 \times 10^3}$$

$$= 1 \times 10^{-4}$$

$$= 100 \times 10^{-6}, \text{ or } 100 \mu\text{F}.$$

Note that C_2 has a large value, 100 μF in this example. This is a much higher coupling capacitor value than that found in vacuum tube amplifiers. It is required because of the low input impedance of a transistor stage. Generally, electrolytic capacitors are used for coupling and bypassing in transistor amplifiers because of their characteristics of containing large capacitance values in small packages. However, the polarity of electrolytic capacitors must be observed to properly connect them into a circuit.

The value of the coupling capacitor controls the low-frequency response. The stray circuit capacitance represents a shunt element, but has less effect in the high-frequency response of transistor circuitry than it does in tube circuits because of the much lower impedances in the transistor circuits. The characteristics of the transistors usually determine the high-frequency response limit. Transistor manufacturer specification sheets generally indicate the frequency at which the current gain of the transistor drops to .707 of β . This is called the cutoff frequency (commonly designated f_β or $f_{h(e)}$). The frequency at which the current gain of the transistor drops to one, or unity, is also usually specified. This frequency, often designated f_T , is equal to the product of β multiplied by the transistor cutoff frequency. It is also known as the gain-bandwidth product, even though it is equal to the gain multiplied by only the high-end frequency of the bandwidth. In this context, therefore, bandwidth is defined as only the cutoff frequency.

Therefore:

$$f_T = \beta \times f_{\beta}, \text{ or}$$

$$f_T = h_{fe} \times fh_{fe}.$$

Because of the inconsistencies in designations of characteristics from different manufacturers, this information is intended only as a general explanation of these common parameters.

In all Class A amplifiers, the dc operating voltages and currents do NOT change. Measurements of dc voltages and currents will indicate constant values with or without signals applied to the transistors. RC amplifiers of this type usually provide relatively large voltage and current gain.

Impedance Coupling

Figure 25 shows the circuit of a transistor amplifier with **IMPEDANCE COUPLING**. The signal is coupled from the first stage to the second stage in the same way in the impedance-coupled circuit as it is in the resistance-capacitance coupled circuit. This circuit is similar to the circuit shown in

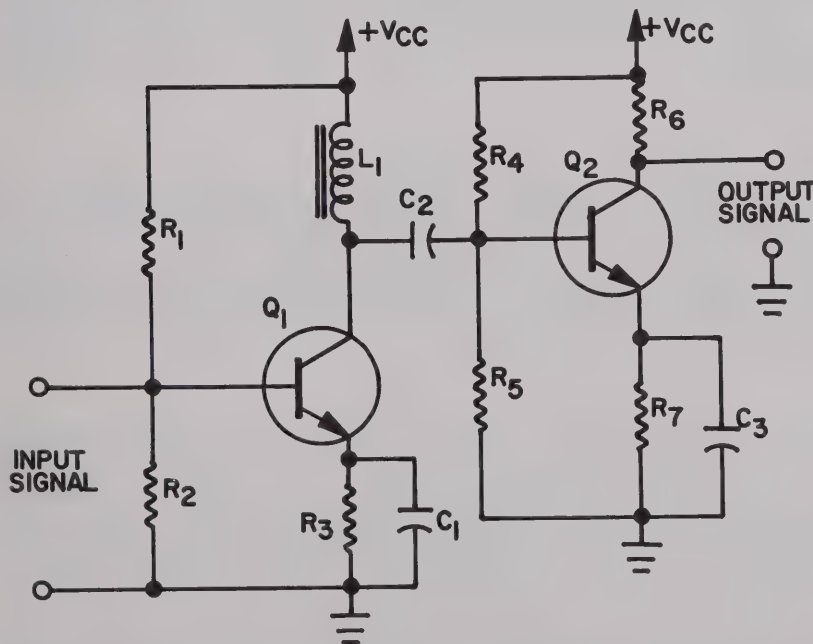


Figure 25

Figure 24, except that collector load coil L_1 replaces load resistor R_3 of Figure 24.

Impedance coupling functions in a manner that is similar to that of resistance-capacitance coupling. The lower dc resistance of the inductor causes a smaller loss of power supply energy. However, the self-inductance of L_1 varies with frequency, and therefore, the Q_1 collector load impedance develops a signal voltage that varies with changing frequency. An impedance-coupled amplifier does not have the same response to all frequencies. It tends to produce a larger output at high frequencies than it does at low frequencies. Impedance coupling is especially suited to applications in which the signal consists of only a single frequency or a narrow band of frequencies.

Direct Coupling

At very low signal frequencies, the reactance of the coupling capacitor prevents most of the signal from being coupled to the next stage. If the input signal is a shift in dc voltage, the coupling capacitor passes the signal only during the period of changing voltage. The steady state dc voltage does not appear at any point following the capacitor.

The same is true regarding transformer coupling. Any voltage induced in the secondary winding results from changes in the primary current. When the current is steady because of a constant value or a dc input signal, no output voltage is induced. Therefore, a dc signal cannot be coupled by a transformer.

When the signals that we wish to amplify are of very low frequencies or are dc, the previously mentioned coupling methods are not suitable. In most cases, a method known as **DIRECT COUPLING** is used to transfer the desired signal between stages. Direct coupling action is simpler than that of any of the other coupling methods, but the circuit design and component tolerance values are more critical.

A direct-coupled amplifier using two NPN transistors is shown in Figure 26. The collector of Q_1 is coupled directly to the base of Q_2 . Resistor R_3 serves as both the collector load resistor for Q_1 and the base bias resistor for Q_2 . Changes of Q_1 collector current vary the voltage across R_3 , causing corresponding changes of Q_1 collector voltage and Q_2 base voltage.

Because there is no capacitor to isolate the Q_1 collector from the Q_2 base, the circuit presents the problem of obtaining the desired base and collector

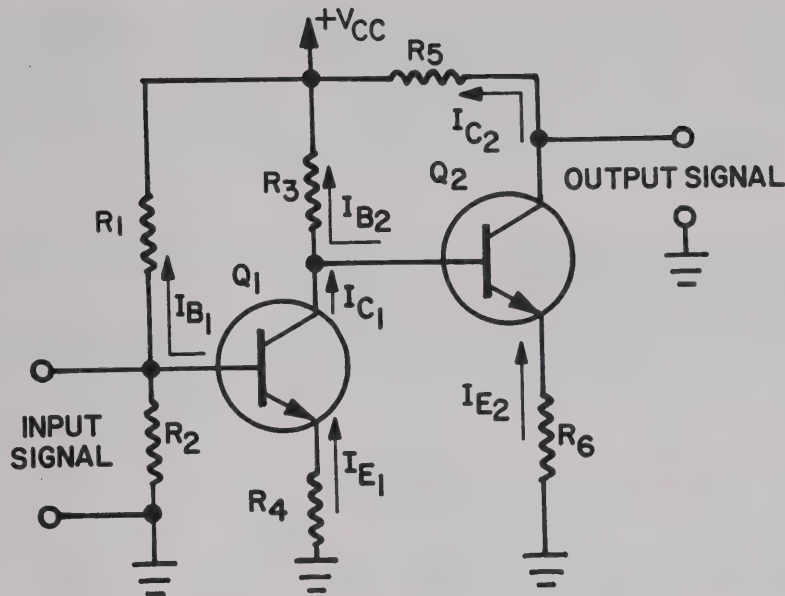


Figure 26

voltages for both transistors. Resistor R_3 carries both the collector current of Q_1 and the base bias current of Q_2 . Its resistance must be selected so that the voltage drop across it will place the voltage at its lower end high enough to make the Q_1 collector sufficiently positive, but not so high that the base of Q_2 is too positive. The value of R_6 is chosen so that the voltage at the Q_2 emitter will be high enough to permit the proper forward bias on the base-emitter junction of Q_2 .

The resistance values of R_1 , R_2 and R_4 are selected to provide the proper value of forward bias on Q_1 . Finally, the resistance of R_5 is selected to provide the desired Q_2 collector current and voltage. Both transistors are now biased properly, with the base-emitter junctions forward biased and the collector-base junctions reverse biased.

Assume that an input signal causes the base of Q_1 to become more positive. This increases the base bias current of Q_1 . The Q_1 collector current increases and develops a larger voltage drop across R_3 . This lowers the voltage on the Q_1 collector and the Q_2 base, and reduces the forward bias on Q_2 , decreasing the Q_2 current. With less Q_2 collector current through R_5 , the voltage across R_5 decreases, and the output voltage at the Q_2 collector becomes more positive. Although the voltage amplification between two direct-coupled transistor stages may be only moderate, the high current gain of common-emitter circuits can still be obtained.

PNP and NPN transistors require similar values of bias voltages, but the voltages must have opposite polarities. If Q_1 and Q_2 of Figure 26 are both replaced by PNP transistors, the polarity of the collector supply must be reversed so that the bases and the collectors are biased negative with respect to the emitters.

Since PNP and NPN transistors require opposite bias voltages, they are said to be COMPLEMENTARY. The complementary condition makes it possible to use both types of transistors in the same circuit so that the collector current of the first stage develops the base bias for the second stage.

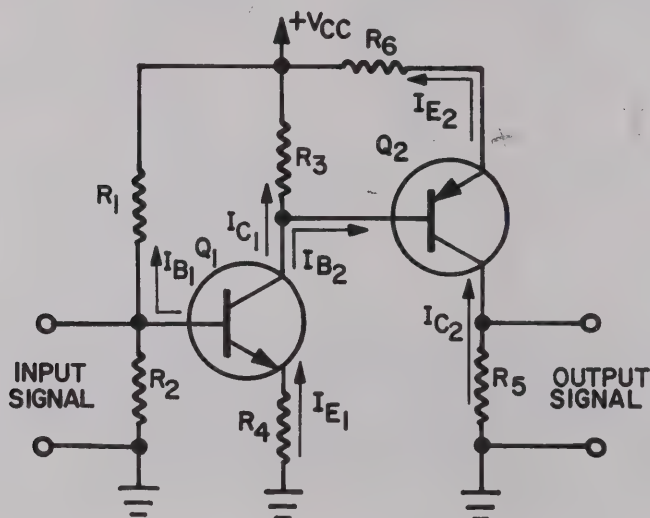


Figure 27

Figure 27 shows a direct-coupled amplifier which uses an NPN transistor in the first stage and a PNP transistor in the second stage. The amplifying and the coupling action is the same as in Figure 26. Because both types of transistors are used, the bias arrangement is different than that of Figure 26.

For the NPN transistor circuit of Q_1 , the resistance values of R_1 , R_2 , R_3 and R_4 are chosen so that Q_1 is properly forward biased and provides the desired value of collector current.

The collector of PNP transistor Q_2 is connected through R_5 to ground (the negative terminal of V_{CC}). This properly reverse biases the collector junction.

tion of Q_2 . Notice that the base and the emitter of Q_2 connect to the positive terminal of V_{CC} through R_3 and R_6 , respectively. The currents through R_3 and R_6 determine the bias of the base-emitter junction of Q_2 . Q_1 collector current is through load resistor R_3 , and Q_2 base and collector currents are through R_6 . The voltage drop across R_3 is greater than that across R_6 . Therefore, the base of Q_2 is negative with respect to its emitter, and Q_2 is properly forward biased. In this type of circuit, Q_2 is said to be operated "upside down."

Direct-coupled amplifiers provide more uniform gain over the low-frequency range than transformer, resistance-capacitance or impedance-coupled amplifiers. Direct-coupled amplifiers can also be used with dc signals. However, the operating points of the transistors become more critical, because some of the resistors carry currents for more than one transistor. A small deviation from normal operation of one transistor can cause a large deviation in following stages. As a result, direct coupling often requires negative feedback and expensive precision components. Note that the emitter resistors in Figures 26 and 27 are unbypassed, providing negative current feedback for both Q_1 and Q_2 . This feedback aids significantly in obtaining good stability.

SUMMARY

Transistors are usually connected in one of three circuit arrangements: common-emitter, common-base or common-collector. The common-emitter circuit is the most widely used of the three. It provides large current and voltage gains, the largest power gain and a 180° voltage signal phase reversal. The common-base and common-collector circuits do not provide phase reversal between input and output voltage signals. Common-collector circuits provide current amplification and common-base circuits provide voltage amplification.

To operate correctly, a transistor must be supplied certain voltages (or biases) for each of its elements. Various bias circuits are used for this purpose. Most common bias arrangements use voltage dividers to supply the needed voltages.

The bias determines the class of operation for a transistor. In Class A operation, the transistor conducts for the full input signal cycle. In Class B operation, the transistor conducts for about half of the input signal cycle. Class AB operation occurs between Classes A and B. In Class C operation, the transistor conducts for appreciably less than half of the input signal cycle.

In some cases, it is necessary to obtain more gain than can be provided by one transistor. Several transistors are coupled together so that the output of one transistor is amplified again by the following transistor. Common methods of coupling transistor stages are transformer coupling, resistance-capacitance coupling, impedance coupling and direct coupling.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

METHODS OF COUPLING

TRANSFORMER COUPLING

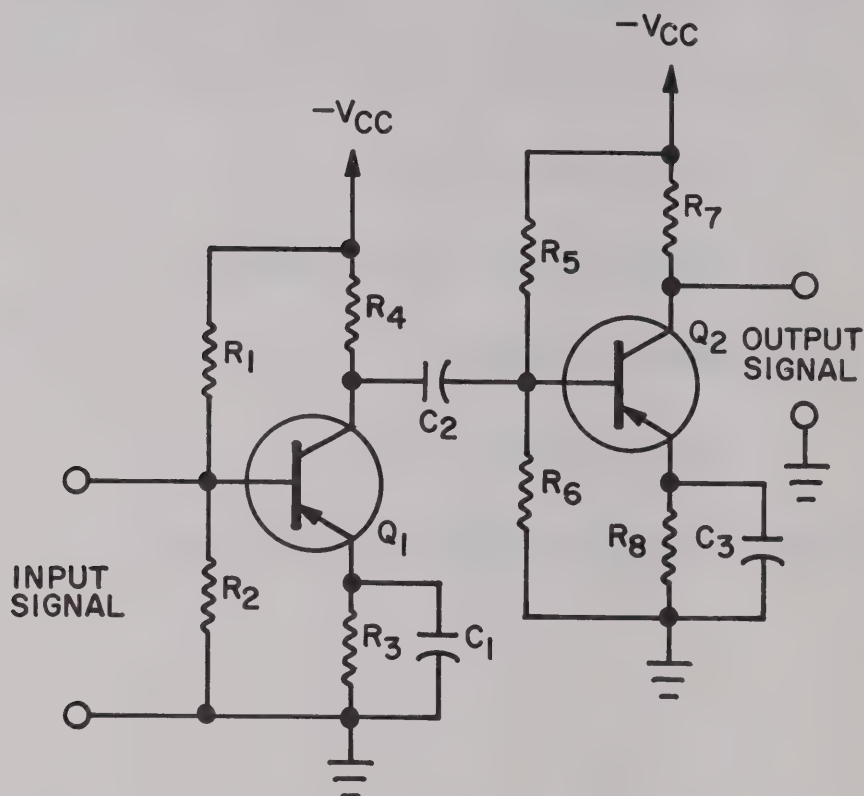
RESISTANCE-CAPACITANCE COUPLING

IMPEDANCE COUPLING

DIRECT COUPLING

41. Draw a circuit like that of Figure 23 using NPN transistors.
42. What is an advantage of transformer coupling?
43. What is the function of C_1 in Figure 23?
44. As the Q_1 collector voltage in Figure 24 decreases, capacitor C_2 charges. True or False?
45. What is the phase relationship between the input and output signals in the circuit of Figure 24?

46. Referring to the following circuit, explain circuit action when the input signal becomes less negative.



47. For proper operation, the time constant of the RC coupling circuit should be short. True or False?
48. In a transistor audio amplifier, would you expect the coupling capacitor to have a value of $.1 \mu\text{F}$ or $50 \mu\text{F}$?
49. How does impedance coupling differ from RC coupling?
50. At what signal frequencies are direct-coupled amplifiers employed?
51. In the circuit of Figure 26, what is the relation between the voltage at the collector of Q_1 and the voltage drop across R_6 for proper bias on Q_2 ?
52. In the circuit of Figure 27, is the voltage drop across R_3 greater or less than the voltage drop across R_6 for proper bias on Q_2 ?

IMPORTANT DEFINITIONS

CLASS A AMPLIFIER — An amplifier in which the operating point is chosen so that there is collector current during the entire input signal cycle (360°).

CLASS AB AMPLIFIER — An amplifier in which the operating point is chosen so that there is collector current for more than half but less than the entire input signal cycle (between 180° and 360°).

CLASS B AMPLIFIER — An amplifier in which the operating point is chosen so that there is collector current for almost half of the input signal cycle (approximately 180°).

CLASS C AMPLIFIER — An amplifier in which the operating point is chosen so that there is collector current for considerably less than half of the input signal cycle (less than 180°).

COMMON-BASE (CB) AMPLIFIER — A transistor amplifier circuit in which the base is the common or grounded element. The input is applied to the emitter, and the output is taken at the collector.

COMMON-COLLECTOR (CC) AMPLIFIER — A transistor amplifier circuit in which the collector is the common or grounded element. The input is applied to the base, and the output is taken at the emitter. Also called an emitter follower.

COMMON-EMITTER (CE) AMPLIFIER — A transistor amplifier circuit in which the emitter is the common or grounded element. The input is applied to the base, and the output is taken at the collector.

COUPLING — The process of transferring a signal from one stage to the next stage.

DIRECT COUPLING — A method of transferring a signal from one point to another by means of a conductive connection.

GAIN — The ratio of the output signal voltage, current or power of an amplifier to the input signal voltage, current or power of the amplifier.

IMPEDANCE COUPLING — A method of transferring a signal between stages in which an inductor is the load component in one stage, resistors are the input components in the other stage, and a capacitor provides a path for the signal between the two stages.

IMPORTANT DEFINITIONS (Continued)

LINEAR AMPLIFIER — An amplifier that operates only on the straight part of the characteristic transfer curve.

POWER AMPLIFIER — An amplifier designed to supply a load that requires both high current and voltage signals.

RESISTANCE-CAPACITANCE (RC) COUPLING — A method of transferring a signal between stages, in which resistors form the output load of one stage and the input circuit of the other stage. A capacitor provides a path for the signal between them.

TRANSFORMER COUPLING — A method of transferring a signal by applying the output of the source to the primary of a transformer and taking the input to the load from the secondary.

VOLTAGE AMPLIFIER — An amplifier designed primarily to supply a large voltage signal to the load.

ESSENTIAL SYMBOLS AND EQUATIONS

A_I	Current gain
A_P	Power gain
A_V	Voltage gain
E_{ff}	Percent efficiency
$I_{C(AVE)}$	Average collector current
I_{IN}	Input signal current
I_{OUT}	Output signal current
P_{dc}	DC input to the amplifier stage from the power supply
P_{IN}	Input power
P_{OUT}	Output power
V_{CC}	Collector supply voltage
V_{IN}	Input signal voltage
V_{OUT}	Output signal voltage
Z_1	Impedance (larger)
Z_2	Impedance (smaller)

$$A_V = \frac{V_{OUT}}{V_{IN}} \quad (1)$$

$$A_I = \frac{I_{OUT}}{I_{IN}} \quad (2)$$

$$A_P = \frac{P_{OUT}}{P_{IN}} = A_V \times A_I \quad (3)$$

$$E_{ff} = \frac{P_{OUT}}{P_{dc}} \times 100 \quad (4)$$

$$P_{dc} = I_{C(AVE)} \times V_{CC} \quad (5)$$

$$N^2 = \frac{Z_1}{Z_2} \quad (6)$$

PRACTICE EXERCISE SOLUTIONS

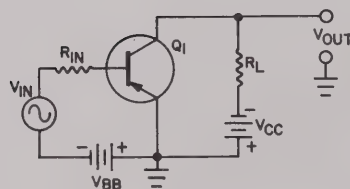
1. A voltage amplifier is used to supply a large output voltage signal with little output current. A power amplifier, on the other hand, supplies a large output current signal to the load.
2. The voltage gain is equal to:

$$A_V = \frac{V_{OUT}}{V_{IN}} = \frac{10 \text{ volts}}{.5 \text{ volt}} = 20.$$

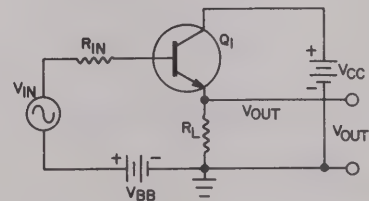
3. To determine the power output, the power gain formula must be re-arranged:

$$A_P = \frac{P_{OUT}}{P_{IN}} \text{ or } P_{OUT} = A_P P_{IN} = 12 \times .3 \text{ watt} = 3.6 \text{ watts.}$$

4. The common-collector (emitter-follower) amplifier provides the highest input impedance and the lowest output impedance and therefore would serve best as a circuit to match a high source impedance to a low load impedance.
5. emitter — The common-emitter amplifier provides the highest power gain because both the voltage and the current gains are high.
- 6.



PNP COMMON-EMITTER AMPLIFIER

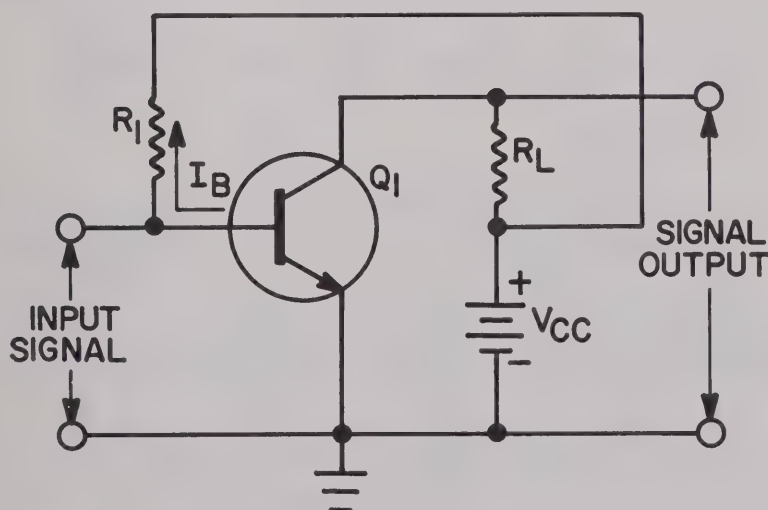


NPN COMMON-COLLECTOR AMPLIFIER

7. When the input signal makes the base of Q_1 less positive, the forward bias on Q_1 decreases, thus decreasing base current. As a result, collector current decreases and the voltage drop across R_L decreases. Since the output voltage is the difference between V_{R_L} and V_{CC} , it increases, or becomes more positive.
8. In a common-emitter amplifier, the input and output signal voltages are 180° out-of-phase.
9. The function of resistor R_L is to develop the output signal. Collector current changes in R_L develop the varying output signal voltage.

PRACTICE EXERCISE SOLUTIONS (Continued)

10. In a PNP common-emitter circuit, the input voltage and the collector current are in phase. The same is true in an NPN common-emitter circuit. However, the collector voltages in these circuits are out-of-phase with the input voltages.
11. less — As the input signal drives the base more negative, the base current increases. As a result, collector current and the voltage drop across the load resistor increase. In turn, the output voltage decreases.
12. $V_{OUT} = V_{CC} - V_{R_L}$. — The output voltage is the difference between the collector supply voltage and the voltage drop across the load resistor.
13. The input and output voltage signals are in phase in both common-base and common-collector amplifiers.
14. The output voltage signal in a common-collector amplifier is developed by the signal current in the load resistor, R_L . As the collector current varies, the voltage drop across R_L varies.
15. Yes — In the common-base circuit, as well as the common-emitter circuit, the output voltage is the difference between the collector supply and the voltage developed across the load resistor.
- 16.

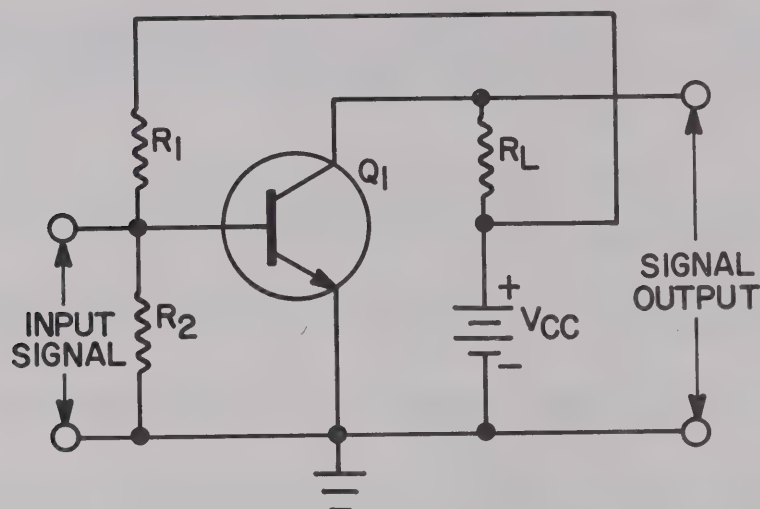


17. The value of base current is equal to $60 \mu\text{A}$:

$$I_B = \frac{V_{CC}}{R_1} = \frac{9 \text{ Volts}}{1.5 \times 10^5 \text{ ohms}} = 6 \times 10^{-5} = 60 \text{ microamperes.}$$

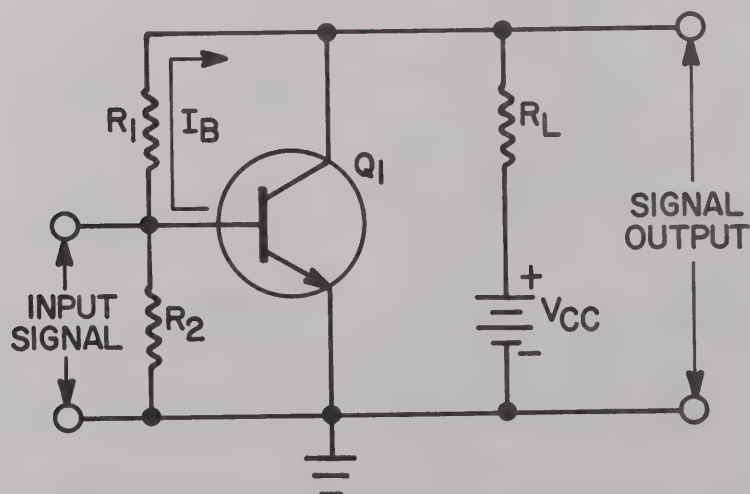
PRACTICE EXERCISE SOLUTIONS (Continued)

18.



19. As base current increases, the voltage drop across R_1 increases. This reduces the voltage drop across R_2 , reducing the forward bias. This action tends to limit any increase in base current.
20. Stability is improved with small values of R_2 . However, decreasing the value of R_2 causes more of the input signal to be shunted, because the input impedance of the circuit is reduced.

21.



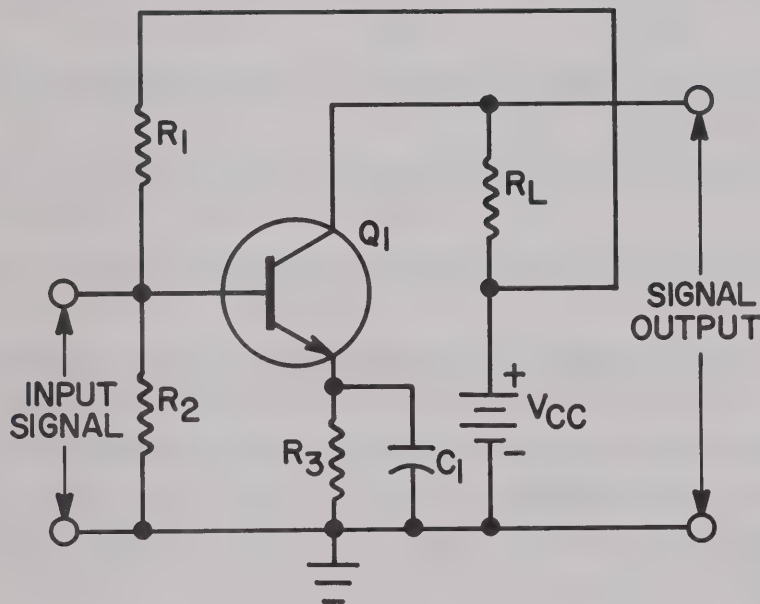
22. A decrease in the collector current decreases the voltage drop across R_L and thus increases the collector voltage. Since the bias circuit is connected to the collector, the bias is increased. The resultant increase in the base current tends to return the collector voltage to its former value.

PRACTICE EXERCISE SOLUTIONS (Continued)

23. 3.7 —

$$\begin{aligned} A_v &= \frac{R_L}{R_3} \\ &= \frac{10,000}{2700} \\ &= 3.7 \end{aligned}$$

24.

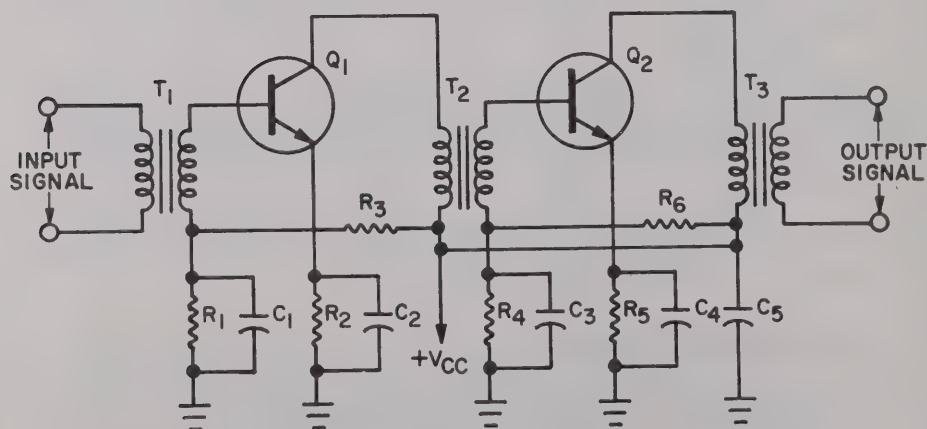


25. False — Increasing the drop across R_3 reduces the forward bias on the emitter junction.
26. The base-emitter voltage, V_{BE} , in circuit A is $6.4V - 6.2V$, or .2 volt, and therefore, the transistor is germanium. In circuit B, the base-to-emitter voltage is $9V - 8.3V$, or .7 volt, and therefore, the transistor is silicon.
27. A Class A amplifier is one in which there is collector current for the full 360° of the input signal cycle.
28. The current gain is equal to:

$$A_I = \frac{I_{OUT}}{I_{IN}} = \frac{4 \times 10^{-3}}{15 \times 10^{-6}} = 267 \text{ (approximately).}$$

PRACTICE EXERCISE SOLUTIONS (Continued)

29. The efficiency of an amplifier is the ratio of signal output power to dc power input from the power supply.
30. The efficiency of a Class A amplifier is approximately 30%.
31. A Class A amplifier has low distortion.
32. A Class B amplifier is one that is biased so that it conducts collector current for about 180° of the input signal cycle.
33. Yes
34. The maximum efficiency of a Class B amplifier is about 78%.
35. A transistor amplifier is biased near or a little above cutoff for Class B operation.
36. A Class AB amplifier is an amplifier biased so that there is collector current for more than 180° but less than 360° of the input signal cycle.
37. The efficiency of a Class AB amplifier is greater than that of a Class A but less than that of a Class B amplifier.
38. A Class C amplifier is an amplifier biased so that there is collector current for considerably less than 180° of the input signal cycle.
39. The maximum efficiency of a Class C amplifier is approximately 85%.
40. Class AB. — The transistor is biased inside of cutoff so that there is collector current for more than 180° , but less than 360° , of the input signal cycle.
- 41.



PRACTICE EXERCISE SOLUTIONS (Continued)

- 42. Transformer coupling has the advantage of providing a good impedance match between stages.
- 43. C_1 is a bypass capacitor which prevents signal voltage from appearing across R_1 .
- 44. False — Capacitor C_2 charges when the Q_1 collector voltage increases and discharges when the Q_1 collector voltage decreases.
- 45. The input and the output signals in the circuit of Figure 24 are in phase, since each stage produces a 180° phase shift for a total phase shift of 360° .
- 46. When the input signal becomes less negative, the Q_1 base current decreases, reducing Q_1 collector current, and increasing the Q_1 collector voltage. As a result, C_2 charges. The C_2 charge current drives the base of Q_2 more negative, increasing base current. Q_2 collector current increases, with a resultant decrease in collector voltage.
- 47. False — The time constant should be long with respect to the period of the lowest signal frequency.
- 48. $50\ \mu\text{F}$. — Due to the lower input and output impedances, the coupling capacitors in transistor circuits generally have a high value, like $50\ \mu\text{F}$.
- 49. The difference between impedance and RC coupling is that an inductor is used in place of the load resistor in an impedance-coupled stage.
- 50. Direct-coupled amplifiers are generally used at very low signal frequencies, and where the signals are actually variations in dc levels.
- 51. The voltage of the collector of Q_1 must be greater by V_{BE} of Q_2 than the voltage drop across R_6 for proper bias on Q_2 .
- 52. The voltage drop across R_3 must be greater than the voltage drop across R_6 for proper operation. Remember, Q_2 is a PNP transistor, and the base must be negative in respect to the emitter for forward bias.

NOTICE: To keep our lessons up-to-date, we add material to the texts from time to time, and make occasional changes in the examination questions. Therefore, when checking your answers with this check sheet, look at the code LETTER (A, B, C, etc.) on your examination sheet to determine which of the following groups of answers apply to the lesson which you have.

1079C&D

1. A - IN A CLASS A AMPLIFIER, THERE IS COLLECTOR CURRENT FOR -- 360° OF THE INPUT CYCLE.
In a Class A amplifier, the bias and signal level are set so that there is collector current for the full input cycle.

2. C - A COMMON-EMITTER AMPLIFIER -- HAS A HIGH VOLTAGE GAIN.

A common-emitter amplifier has high voltage and current gain, a 180° phase reversal of the signal voltages, a moderate input impedance and a moderate output impedance.

3. D - AN INCREASE IN THE TEMPERATURE OF A TRANSISTOR -- INCREASES TRANSISTOR CURRENT GAIN.

An increase in temperature increases the number of current carriers in the semiconductor material which causes an increase in the current gain (β) of the transistor.

4. C - SUPPOSE THAT V_{CC} IN THE CIRCUIT OF FIGURE 7 IS 12 VOLTS. ASSUMING THAT THE BASE-TO-EMITTER VOLTAGE DROP OF Q_1 IS NEGLIGIBLE, WHAT VALUE OF R_1 IS REQUIRED FOR A BASE CURRENT OF 100 μA ? -- 120 k Ω .

The value of R_1 is found by using Ohm's Law.

$$R_1 = \frac{V_{CC}}{I_B} = \frac{12 \text{ volts}}{100 \times 10^{-6} A} = \frac{12}{1 \times 10^{-4}} = 12 \times 10^4 = 120 \text{ k}\Omega.$$

5. B - R_3 IN THE CIRCUIT OF FIGURE 12 -- PROVIDES NEGATIVE FEEDBACK.

The emitter resistor is generally a low value resistor that provides degenerative feedback. This negative current feedback stabilizes the circuit.

6. D - A TRANSISTOR AMPLIFIER IS OPERATED SUCH THAT THE COLLECTOR CURRENT FLOWS FOR APPROXIMATELY 180° OF THE INPUT CYCLE. THE CIRCUIT IS THUS OPERATING -- CLASS B.

The transistor is operating near cutoff which is the bias point for Class B operation.

7. D - IN THE RC COUPLED AMPLIFIER OF FIGURE 24 -- C_2 DISCHARGES WHEN Q_1 COLLECTOR CURRENT INCREASES.

The coupling capacitor, C_2 , discharges when Q_1 collector current increases because the voltage drop across R_3 increases thus reducing the collector voltage.

8. D - WITH RESPECT TO AN RC-COUPLED AMPLIFIER, -- INCREASING THE VALUE OF THE COUPLING CAPACITOR IMPROVES THE LOW-FREQUENCY RESPONSE.

The coupling capacitor forms part of a high-pass filter with the low frequency cutoff point determined by the value of the coupling capacitor.

9. A - IF C_3 IS REMOVED IN THE CIRCUIT OF FIGURE 25 -- THE OUTPUT SIGNAL AMPLITUDE WILL DECREASE.

Removing C_3 introduces negative feedback into the circuit which reduces the Q_2 stage gain, thus reducing the output signal amplitude.

10. D - REFERRING TO THE CIRCUIT OF FIGURE 27, IF THE COLLECTOR VOLTAGE ON Q_1 IS +3 VOLTS AND THE EMITTER VOLTAGE ON Q_2 IS +3.7 VOLTS, -- Q_2 IS CONDUCTING.

Since Q_2 is a PNP transistor, the base must be less positive than the emitter in order to have Q_2 forward biased. Since this condition does exist Q_2 is forward biased and is conducting.

1079B

All explanations are the same as for 1079C except for those given below.

1. A - IN A CLASS A AMPLIFIER, COLLECTOR CURRENT FLOWS FOR -- 360° OF THE INPUT CYCLE.

In a Class A amplifier, the bias and signal level are set so that collector current flows for the full input cycle.

3. D - AN INCREASE IN THE TEMPERATURE OF A TRANSISTOR -- INCREASES COLLECTOR CURRENT.

An increase in temperature increases the number of current carriers in the semiconductor material which causes an increase in base and collector current.

1079A,B,C&D

EXPERIMENT 7

CLASS A AND B TRANSISTOR AMPLIFIERS

PARTS NEEDED

- | | |
|---|--|
| 1 - Complete Design Console | 2 - 10 k Ω , 1/2 W, 20% Resistors |
| 1 - Multimeter with Test Leads and Spring Adapters | 1 - 100 k Ω , 1/2 W, 20% Resistor |
| 1 - 1 M Ω Potentiometer with Bracket and Leads | 1 - 220 k Ω , 1/2 W, 20% Resistor |
| 1 - Transistor Socket with Leads | 6 - Modular Connectors |
| 1 - NPN Transistor | 2 - Tri-mounts |
| | - No. 22 Solid Hookup Wire |

OBJECTIVE

In this experiment you will examine the basic operating characteristics of Class A and Class B transistor amplifiers.

PROCEDURE

1. Set up the common-emitter amplifier circuit of Figure 7-1 following the layout of Figure 7-2. Set R_3 fully counterclockwise and the ADJUST VOLTAGE control on the design console fully counterclockwise. Do not connect the audio generator lead to R_4 at this time. Set the ADJUST FREQ. control to 5. Turn on the design console and set the regulated power supply switch to the 30V position. Set the ADJUST VOLTAGE control on the design console for a regulated dc voltage of 15 volts.

2. As in the case of a vacuum tube amplifier, a transistor can be set for Class A operation by adjusting the dc bias so that the dc collector voltage is about one-half of the supply voltage.

While measuring the Q_1 collector voltage, adjust R_3 clockwise until the collector voltage is one-half of the supply voltage (7.5 volts dc).

3. In a Class A tube or transistor amplifier, the dc operating conditions do not shift when a signal is applied. While monitoring the Q_1 dc collector voltage, connect the sinewave output of the audio generator to R_4 to apply an input signal. R_4 limits the signal to the Q_1 base circuit to prevent overload. Note that the Q_1 dc collector voltage does not change appreciably.

4. Measure the ac signal at the collector of Q_1 with the output function of your multimeter and record it here.

Output Signal = _____ volts ac

Class A and B Transistor Amplifiers

5. To operate a transistor amplifier Class B, the bias should be set so that there is an output signal for about 180 degrees of the input cycle. There is often confusion as to whether a transistor operates Class B or Class C with zero bias. For Class C operation, there would be an output signal for significantly less than 180 degrees of the input signal. Remember, it takes a definite amount of forward bias voltage for conduction (silicon = 0.6 volt, germanium = 0.3 volt). The large amplitude signal used here in Step 5 will produce Class B operation.

Disconnect the audio generator output from R_4 . To set the circuit of Figure 7-1 for Class B operation, measure the Q_1 dc collector voltage and adjust R_3 counterclockwise until the collector voltage just reaches 15 volts, the supply voltage. Do not exceed this point or you will bias the circuit for Class C operation.

6. While measuring the Q_1 dc collector voltage, reconnect the audio generator output to R_4 . Note that the dc collector voltage decreases, indicating the normal shift in dc conditions in a Class B amplifier when a signal is applied.

7. Measure the ac signal at the collector of Q_1 , and note that it is less than that observed in Step 4 for Class A operation. However, the output signal is not half as much as it was in the Class B vacuum tube circuit. This is caused by a change in the input impedance of the circuit from Class A to Class B operation. This changes the input signal level, thus affecting the output signal amplitude.

CONCLUSION

As in vacuum tube circuits, Class A transistor amplifiers have higher voltage gains than do Class B circuits. The dc operating conditions remain relatively constant in a Class A amplifier when a signal is applied. In a Class B circuit, the collector voltage decreases when a signal is applied.

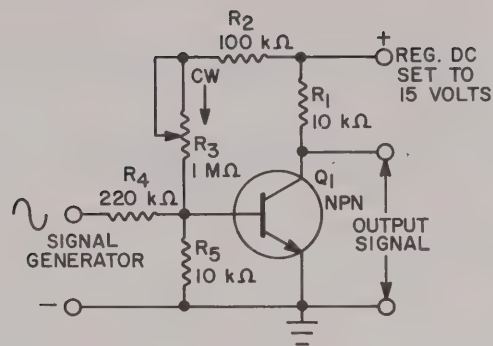
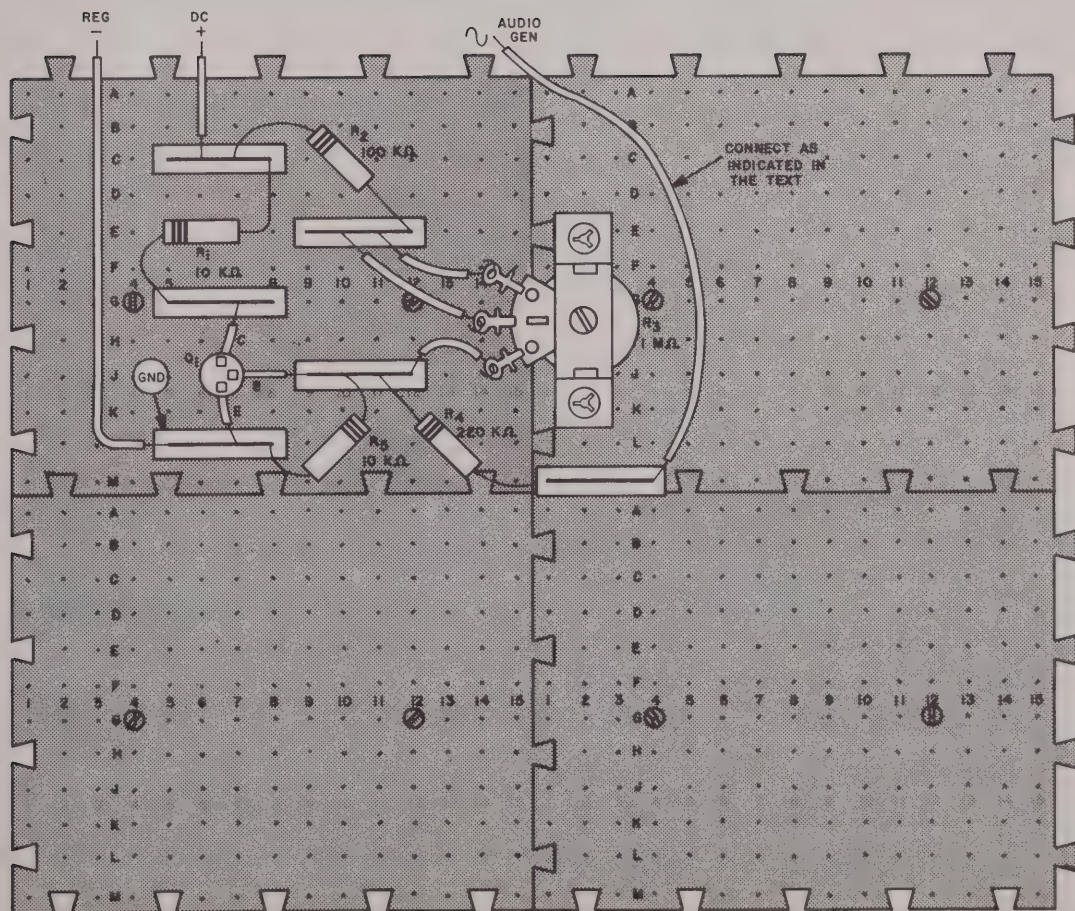


FIGURE 7-1



NOTES



ONE OF THE

BELL & HOWELL SCHOOLS

9506-7B

9506-7A&B
EXAMINATION
CHECK SHEET

1. D - THE ZERO BIASED TRANSISTOR AMPLIFIER OF STEP 5 OPERATES -- CLASS B.
Since the relatively large input signal causes a signal output for about 180 degrees of the input cycle, the amplifier stage is operating Class B.

2. B - SUPPOSE THAT THE EMITTER VOLTAGE OF A CLASS A PNP TRANSISTOR AMPLIFIER IS -1.3 VOLTS. ASSUMING A SILICON TRANSISTOR, WHAT DC VOLTAGE WOULD YOU EXPECT AT THE BASE? -- -1.9 VOLTS.
With the normal 0.6 volt bias for a silicon transistor, the base voltage must be -1.3 volts plus -0.6 volt or -1.9 volts.

3. D - IN A CLASS A TRANSISTOR AMPLIFIER, COLLECTOR CURRENT FLOWS FOR -- 360° OF THE INPUT SIGNAL CYCLE.
In a Class A amplifier, collector current flows for the entire input cycle (or 360°).

4. A - IN A CLASS B TRANSISTOR AMPLIFIER, WHEN AN INPUT SIGNAL IS APPLIED, THE DC -- COLLECTOR VOLTAGE DECREASES.
When a signal is applied, collector current increases, decreasing the average dc collector voltage.

5. B - IN A CLASS B TRANSISTOR AMPLIFIER CIRCUIT, COLLECTOR CURRENT FLOWS FOR -- 180° OF THE INPUT SIGNAL CYCLE.
In a Class B amplifier, collector current flows for one half the input cycle or 180° since the transistor is biased at cutoff.

9506-7A

All explanations are the same as for 9506-7B except for that given below.

1. D - A ZERO BIASED TRANSISTOR AMPLIFIER OPERATES -- CLASS C.
Since it takes 0.6 volt for conduction of a silicon transistor and 0.3 volt for conduction of a germanium transistor, a zero biased transistor amplifier actually operates Class C.

9506-7A&B

- 1. ☐ A ☐ B ☐ C ☐ D
- 2. ☐ A ☐ B ☐ C ☐ D
- 3. ☐ A ☐ B ☐ C ☐ D
- 4. ☐ A ☐ B ☐ C ☐ D
- 5. ☐ A ☐ B ☐ C ☐ D
- 6. ☐ A ☐ B ☐ C ☐ D
- 7. ☐ A ☐ B ☐ C ☐ D
- 8. ☐ A ☐ B ☐ C ☐ D
- 9. ☐ A ☐ B ☐ C ☐ D
- 10. ☐ A ☐ B ☐ C ☐ D

UNIT EXAMINATION FOR COURSE 242

This examination contains a number of different type questions: multiple choice, true or false, fill in the blank and direct question. To assist us in grading, please print your answers clearly on the answer sheet. **COMPLETE THE PORTION STATING YOUR NAME, ADDRESS AND STUDENT NUMBER ON THE ANSWER SHEET AND SEND ONLY THE ANSWER SHEET FOR GRADING.** Retain the examination questions for your records.

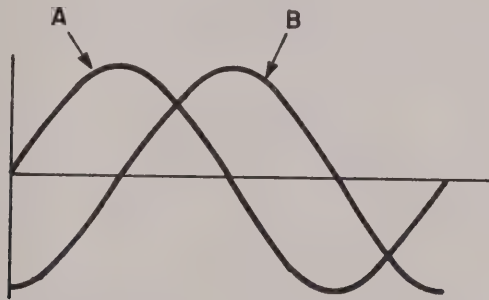


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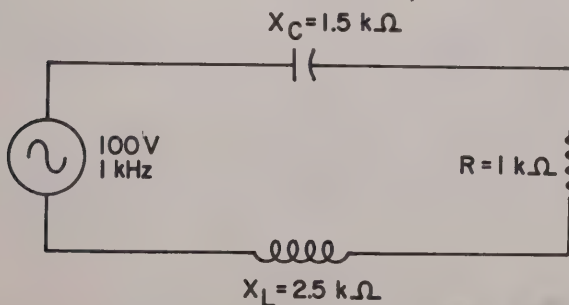
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- What is the required value of the shunt resistor necessary to convert a milliammeter with a full-scale deflection of 1 milliamper and an internal resistance of 50 ohms to a milliammeter which will read 100 milliamperes full scale? 50.5 Ω
- To convert a milliammeter into a voltmeter would you add a resistance in series or in parallel with the meter movement? series
- Voltmeter polarity must be observed when measuring ac voltages. True or False?
- In the diagram shown below,
 (A) waveform A lags waveform B by 90 degrees. (B) waveform B leads waveform A by 90 degrees. (C) waveform A leads waveform B by 90 degrees. (D) waveform A would represent current and waveform B would represent voltage in a purely inductive circuit.



- What is the inductive reactance of a 2.5-henry coil at a frequency of 100 hertz? 1570 Ω
- What is the reactance of a .5 μF capacitor at a frequency of 1 kHz? 318 Ω
- What is the impedance of the series circuit shown below? 1.4 k Ω



$$X_L - X_C = 1k$$

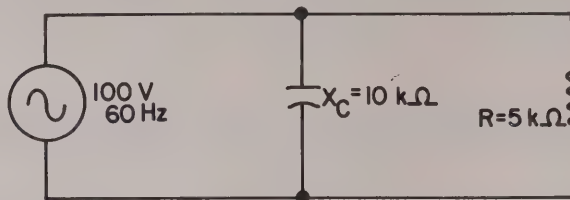
$$Z = \sqrt{10^4 + 10^4}$$

$$= 10^2 \sqrt{2}$$

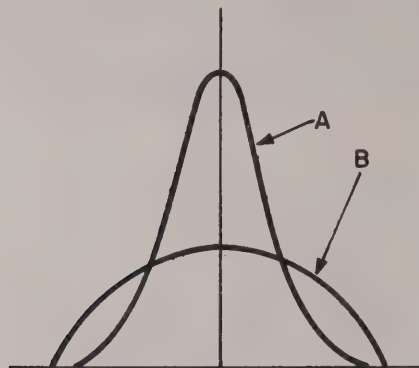
$$= 1.414 \times 10^2$$

UNIT EXAMINATION QUESTIONS 242

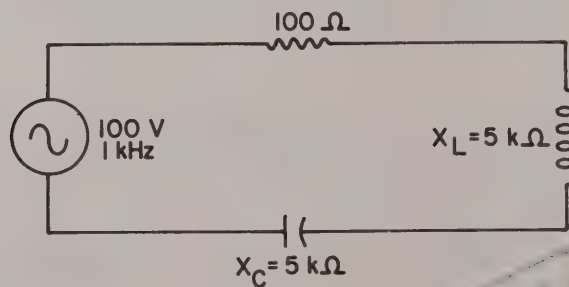
8. What is the impedance of the parallel circuit shown below? $\frac{100 \times 10^4}{\sqrt{5}} \rightarrow 450 \text{ k}\Omega$



9. Which of the response curves shown below would represent the response of a resonant circuit with a high Q? A



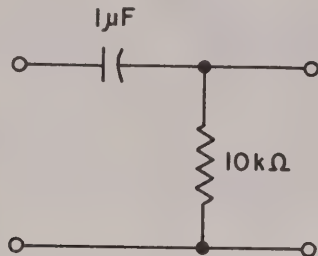
10. What is the resonant frequency of a parallel RLC circuit if $L = 100$ microhenries and $C = 200$ pF? 1.14 MHz
11. Is the impedance of a parallel RLC circuit minimum or maximum at resonance? maximum
12. What is the impedance of the series RLC circuit shown below? 100Ω



13. In a reactive AC circuit,
 (A) true power is always greater than apparent power. (B) the power factor is equal to the true power divided by the apparent power. (C) power factor is equal to the apparent power divided by the true power. (D) reactive power is always greater than apparent power.

14. What is the value of one time constant in the circuit shown below?

10 msec

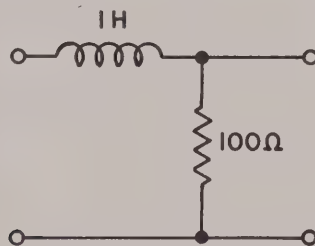


$RC = 10$

15. What is the value of one time constant in the circuit shown below?

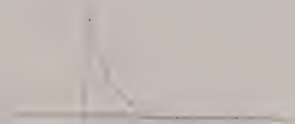
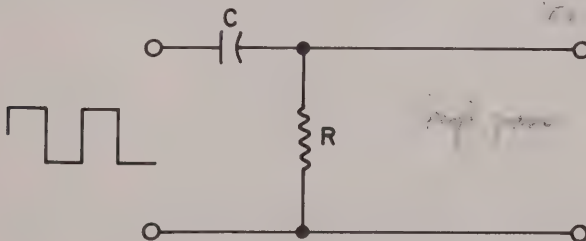
10 msec

10 msec



$\frac{1}{2} = \frac{1}{100} = 10$

16. To obtain a rectangular waveshape at the output terminals in the circuit shown below, should the time constant of the circuit be long or short with respect to the period of the input signal? long



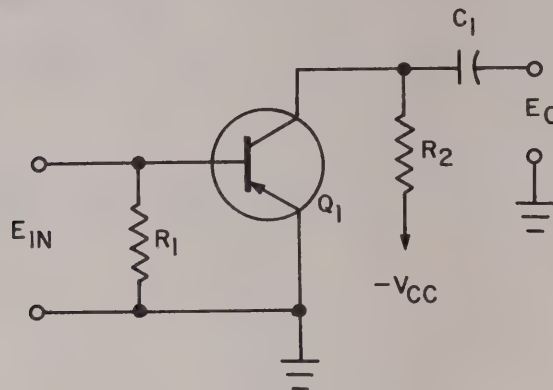
17. What is the name given to the effect that causes current to concentrate at the surface of a conductor at high frequencies? skin effect

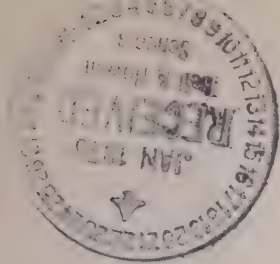
18. The duration of plate current in a Class A amplifier is 180 degrees.

UNIT EXAMINATION QUESTIONS 242

19. Does push-pull operation cancel even or odd harmonic distortion?
even

20. What class of operation is employed in the circuit shown below?
B





UNIT EXAMINATION 242 ANSWER SHEET

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Student No. K36739 16W
UE242A

Write your answers in the space provided. Be sure to include units, such as volts, μF , etc. where necessary.
RETURN ONLY THE ANSWER SHEET FOR GRADING. Keep the exam for your records.

- | | |
|------------------------------------|-------------------------------------|
| 1. <u>.505 Ω</u> | 11. <u>maximum</u> |
| 2. <u>series</u> | 12. <u>100 Ω</u> |
| 3. <u>False</u> | 13. <u>B</u> |
| 4. <u>C</u> | 14. <u>10^{-2} sec</u> |
| 5. <u>1570 Ω</u> | 15. <u>10^{-2} sec</u> |
| 6. <u>318 Ω</u> | 16. <u>long</u> |
| 7. <u>1.4 kΩ</u> | 17. <u>skin effect</u> |
| 8. <u>450 kΩ</u> | 18. <u>360°</u> |
| 9. <u>A</u> | 19. <u>Even</u> |
| 10. <u>1.14 MHz</u> | 20. <u>B</u> |

B.H.S.
8
K.P.

UNIT EXAMINATION 252 ANSWER SHEET



85
FEB 17 1976 GRADE

INSTRUCTOR

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FEB 9 - 1976

Write your answers in the space provided. Be sure to include units, such as volts, μF , etc. where necessary.
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- | | |
|-----------------------------------|---------------------|
| 1. <u>200 Ω</u> | 11. <u>A</u> |
| 2. <u>1,500</u> | 12. <u>Decrease</u> |
| 3. <u>False</u> | 13. <u>low</u> |
| 4. <u>decrease</u> | 14. <u>True</u> |
| 5. <u>x 47.4%</u> | 15. <u>Reverse</u> |
| 6. <u>15 MHz</u> | 16. <u>No</u> |
| 7. <u>C</u> | 17. <u>True</u> |
| 8. <u>False</u> | 18. <u>Increase</u> |
| 9. <u>No</u> | 19. <u>Increase</u> |
| 10. <u>C</u> | 20. <u>C</u> |

